



Regulatory Impact Analysis:

Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements

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Executive Summary

This Regulatory Impact Analysis assesses the feasibility, costs, benefits, cost-effectiveness, and other issues associated with the Environmental Protection Agency's finalized program that sets new federal emission standards for heavy-duty vehicles and places limits on the level of sulfur in diesel fuel. A complete discussion of the details of the program can be found in the preamble to the regulations published in the Federal Register. The key results of this Regulatory Impact Analysis are discussed below.

Health and Welfare Concerns

When revising emissions standards for heavy-duty vehicles, the Agency considers the effects of air pollutants emitted from heavy-duty vehicles on public health and welfare. As discussed in more detail below, the outdoor, or ambient, air quality in many areas of the country is expected to violate federal health-based ambient air quality standards for ground level ozone and particulate matter during the time when this rule would take effect. In addition, some studies have found public health and welfare effects from ozone and PM at concentrations that do not constitute a violation of their respective NAAQS. Other studies have associated diesel exhaust with a variety of cancer and noncancer health effects. Of particular concern is human epidemiological evidence linking diesel exhaust to an increased risk of lung cancer. Emissions from heavy-duty vehicles also contribute to a variety of environmental and public welfare effects such as impairment of visibility/ regional haze, acid deposition, eutrophication/nitrification, and POM deposition. The standards finalized in this rule will result in a significant improvement in ambient air quality and public health and welfare.

Feasibility of Emission Standards

During the past 15 years advancements have continued to be made in the development of diesel exhaust emission control devices. Several emission control devices have emerged to control harmful diesel particulate matter constituents, including the diesel oxidation catalyst and the many forms of particulate filters or traps. Diesel oxidation catalysts have been shown to be durable in-use, but they control only a small fraction of the total particulate matter and consequently do not address our concerns sufficiently. The same is true of un-catalyzed diesel particulate filters. Catalyzed diesel particulate filters have the potential to provide major reductions in diesel particulate matter emissions and provide the durability and dependability required for diesel applications. Precious metal catalyzed particulate filters, in conjunction with low sulfur diesel fuel, have been shown to be more than 90 percent effective over the federal test procedure and the not-to-exceed zone, a level of efficiency that demonstrates a capability of meeting the applicable standards. Therefore, we believe the catalyzed diesel particulate filter will be the control technology of choice for future control of diesel particulate matter emissions.

However, these devices cannot be brought to market on diesel applications unless low sulfur diesel fuel is available.

Several exhaust emission control devices have also been developed to control diesel NO_x emissions. Today's lean NO_x catalyst is capable at best of steady-state NO_x reductions of less than 10 percent, eliminating it from serious consideration as a tool for meeting the future emission standards. Both selective catalytic reduction systems and NO_x adsorbers have the potential to provide significant emission reductions, although we believe that the NO_x adsorber is the most likely candidate to be used to meet future low diesel exhaust emission standards that apply to the heavy-duty diesel market. However, the NO_x adsorber technology cannot be brought to market on diesel engines and vehicles unless low sulfur diesel fuel is available.

These developments make the widespread commercial use of diesel exhaust emission controls feasible. Through the use of these devices, emissions control similar to that attained by gasoline applications will be possible with diesel applications. However, without low sulfur diesel fuel, these technologies cannot be implemented on heavy-duty diesel applications. Low sulfur diesel fuel will at the same time allow these technologies to be implemented on light-duty diesel applications.

Improvements also continue to be made to technologies for controlling emissions from gasoline engines and vehicles. This includes improvements to catalyst designs in the form of improved washcoats and improved precious metal dispersion. Significant effort has also been put into improving cold start strategies that allow for more rapid light-off of the catalyst. These strategies include retarding the spark timing to increase the temperature of the exhaust gases and using air-gap manifolds, exhaust pipes, and catalytic converter shells to decrease heat loss from the system. These improvements to gasoline emission controls will be made in response to recent regulations from California and the EPA that established more stringent emission standards for the light-duty sector. These improvements should transfer well to the heavy-duty gasoline segment of the fleet. With the optimization of these and additional existing technologies for the heavy-duty gasoline sector, we believe that significant reductions in emissions from heavy-duty gasoline engines and vehicles can be realized, thus allowing vehicles to meet more stringent emission standards. The sulfur content of the fuel is a critical ingredient for gasoline engines as well. The Tier 2 gasoline sulfur reduction that requires sulfur levels to be reduced to a 30 parts per million average with an 80 parts per million cap will enable the technology needed to meet the heavy-duty standards in the same way that it enables compliance with the Tier 2 standards.

Fuel Standard Feasibility

In order to meet the 15 parts per million sulfur cap, refiners are likely to further hydrotreat their highway diesel fuel in much the same way as it is being done today to meet the current federal sulfur limits. Improvements to current hydrotreaters can be used to reduce diesel fuel

sulfur beyond that being done to meet the current requirements. However, these improvements alone do not appear to be sufficient to provide compliance with the 15 parts per million cap. Based on past commercial experience, it is very possible to incorporate current distillate hydrotreaters into designs which provide compliance with the proposed 15 parts per million cap. Thus, the equipment added to meet the current requirements in the early 1990's will continue to be very useful in meeting a more stringent standard.

The primary changes to refiners' current distillate hydrotreating systems are likely to be:

- 1) the use of a second reactor to increase residence time, possibly incorporating counter-current flow characteristics, or the addition of a completely new second stage hydrotreater;
- 2) the use of more active catalysts, including those specially designed to desulfurize sterically hindered sulfur containing material;
- 3) greater hydrogen purity and less hydrogen sulfide in the recycle gas; and,
- 4) possible use of higher pressure in the reactor.

Existing commercial hydrotreaters are already producing distillate with average sulfur levels below 10 parts per million, which should be more than sufficient to meet the new requirements. Therefore, the 15 parts per million cap appears to be quite feasible given today's distillate processing technology. Advances continue to be made in catalyst technology, with greater amounts of sulfur being able to be removed at the same reactor size, temperature and pressure. Therefore, it is reasonable to expect that distillate hydrotreaters put into service in the 2006 timeframe will utilize even more active catalysts than those available today.

Other existing methods may help to reduce diesel fuel sulfur levels, but will generally not be sufficient to provide compliance with a 15 parts per million cap. However, we expect that a number of refiners will utilize these techniques to reduce the severity of their distillate hydrotreaters and reduce hydrogen consumption (particularly by avoiding aromatic saturation). Some of these techniques would tend to increase the supply of highway diesel fuel while others would tend to decrease it.

Biodesulfurization technology holds promise to reduce distillate sulfur without the high temperatures and pressures involved in hydrotreating. Efforts are underway to demonstrate that this technology can achieve 50 parts per million sulfur or less in the next few years. However, it is not clear whether this technology would be sufficient to meet a 15 parts per million cap.

In addition, despite the heightened challenge to the distribution industry caused by our sulfur program, it will be feasible to distribute 15 parts per million highway diesel fuel with relatively minor modifications to existing systems to limit contamination from higher sulfur products. These modifications can be accomplished at modest additional costs.

Economic Impact: Diesel Engines

The technologies we expect to be used to meet the new requirements represent significant technological advancements for controlling emissions, but also make clear that much effort remains to develop and optimize these new technologies for maximum emission-control effectiveness with minimum negative impacts on engine performance, durability, and fuel consumption. On the other hand, it has become clear that manufacturers have a great potential to advance beyond the current state of understanding by identifying aspects of the key technologies that contribute most to hardware or operational costs or other drawbacks and pursuing improvements, simplifications, or alternatives to limit those burdens. To reflect this investment in long-term cost savings potential, the cost analysis includes an estimated \$385 million in R&D outlays for heavy-duty engine designs and \$220 million in R&D for catalysts systems giving a total R&D outlay for improved emission control of more than \$600 million. The cost and technical feasibility analyses accordingly reflect substantial improvements on the current state of technology due to these future developments.

Estimated costs are broken into additional hardware costs and life-cycle operating costs. The incremental hardware costs for new engines are comprised of variable costs (for hardware and assembly time) and fixed costs (for R&D, retooling, and certification). Total operating costs include the estimated incremental cost for low-sulfur diesel fuel, any expected increases in maintenance cost or fuel consumption costs along with any decreases in operating cost expected due to low-sulfur fuel. Cost estimates based on these projected technology packages represent an expected incremental cost of engines in the 2007 model year. Costs in subsequent years will be reduced by several factors, as described below. Separate projected costs were derived for engines used in three service classes of heavy-duty diesel engines. All costs are presented in 1999 dollars.

The costs of these new technologies for meeting the 2007 model year standards are itemized in the RIA and summarized in Table V.A-1. For light heavy-duty vehicles, the cost of an engine is estimated to increase by \$1,990 in the early years of the program reducing to \$1,170 in later years and operating costs over a full life-cycle to increase by approximately \$600. For medium heavy-duty vehicles the cost of a new engine is estimated to increase by \$2,560 initially decreasing to \$1,410 in later years with life-cycle operating costs increasing by approximately \$1,200. Similarly, for heavy heavy-duty engines, the vehicle cost in the first year is expected to increase by \$3,230 decreasing to \$1,870 in later years. Estimated additional life-cycle operating costs for heavy heavy-duty engines are approximately \$4,600. The higher incremental increase in operating costs for the heavy heavy-duty vehicles is due to the larger number of miles driven over their lifetime (714,000 miles on average) and their correspondingly high lifetime fuel usage. Emission reductions are also proportional to VMT and so are significantly higher for heavy heavy-duty vehicles.

We also believe there are factors that will cause cost impacts to decrease over time, making it appropriate to distinguish between near-term and long term costs. Our analysis incorporates the effects of this learning curve by projecting that the variable costs of producing the low-emitting engines decrease by 20 percent starting with the third year of production (2009 model year) and by reducing variable costs again by 20 percent starting with the fifth year of production. Additionally, since fixed costs are assumed to be recovered over a five-year period, these costs are not included in the analysis after the first five model years. Finally, manufacturers are expected to apply ongoing research to make emission controls more effective and to have lower operating cost over time. However, because of the uncertainty involved in forecasting the results of this research, we have conservatively not accounted for it in this analysis.

Table ES-1 lists the projected costs for each category of vehicle in the near- and long-term. For the purposes of this analysis, “near-term” costs are those calculated for the 2007 model year and “long term” costs are those calculated for 2012 and later model years.

Table ES-1. Projected Incremental System Cost and Life Cycle Operating Cost for Heavy-Duty Diesel Vehicles (Net Present Values in the year of sale, 1999 dollars)

Vehicle Class	Model Year	Hardware Cost	Life-cycle Operating Cost ^A
Light heavy-duty	near term	\$1,990	\$627
	long term	\$1,170	\$543
Medium heavy-duty	near term	\$2,560	\$1,165
	long term	\$1,410	\$1,007
Heavy heavy-duty	near term	\$3,230	\$4,626
	long term	\$1,870	\$4,030

^A Incremental life-cycle operating costs include the incremental costs to refine and distribute low sulfur diesel fuel, the service cost of closed crankcase filtration systems, the maintenance cost for PM filters and the lower maintenance costs realized through the use of low sulfur diesel fuel (see discussion in Section V.C).

Economic Impact: Gasoline Vehicles

To perform a cost analysis for the final gasoline standards, we first determined a package of likely technologies that manufacturers could use to meet the standards and then determined the costs of those technologies. In making our estimates, we have relied on our own technology assessment which included publicly available information such as that developed by California, confidential information supplied by individual manufacturers, and the results of our own in-house testing.

In general, we expect that heavy-duty gasoline vehicles would (like Tier 2 light duty vehicles) be able to meet these standards through refinements of current emissions control components and systems rather than through the widespread use of new technology. More specifically, we anticipate a combination of technology upgrades such as the following:

- Improvements to the catalyst system design, structure, and formulation, plus an increase in average catalyst size and loading.
- Air and fuel system modifications including changes such as improved oxygen sensors, and calibration changes including improved precision fuel control and individual cylinder fuel control.
- Exhaust system modifications, possibly including air gapped components, insulation, leak free exhaust systems, and thin wall exhaust pipes.
- Increased use of fully electronic exhaust gas recirculation (EGR).
- Increased use of secondary air injection.
- Use of ignition spark retard on engine start-up to improve upon cold start emission control.
- Use of low permeability materials and minor improvements to designs, such as the use of low-loss connectors, in evaporative emission control systems.

We expect that the technologies needed to meet the heavy-duty gasoline standards will be very similar to those required to meet the Tier 2 standards for vehicles over 8,500 pounds GVWR. Few heavy-duty gasoline vehicles currently rely on technologies such as close coupled catalysts and secondary air injection, but we expect they would to meet the new standards.

For each group we developed estimates of both variable costs (for hardware and assembly time) and fixed costs (for R&D, retooling, and certification). Cost estimates based on the current projected costs for our estimated technology packages represent an expected incremental cost of vehicles in the near-term. For the longer term, we have identified factors that would cause cost impacts to decrease over time. First, since fixed costs are assumed to be recovered over a five-year period, these costs disappear from the analysis after the fifth model year of production. Second, the analysis incorporates the expectation that manufacturers and suppliers would apply ongoing research and manufacturing innovation to making emission controls more effective and less costly over time. Our analysis incorporates the effects of this “learning curve” by projecting that a portion of the variable costs of producing the new vehicles decreases by 20 percent starting with the third year of production.

We have prepared our cost estimates for meeting the new heavy-duty gasoline standards using a baseline of current technologies for heavy-duty gasoline vehicles and engines. Finally, we have incorporated what we believe to be a conservatively high level of R&D spending at \$2,500,000 per engine family where no California counterpart exists. We have included this large R&D effort because calibration and system optimization is likely to be a critical part of the effort to meet the standards. However, we believe that the R&D costs may be generous because the projection probably underestimates the carryover of knowledge from the development required to meet the light-duty Tier 2 and CARB LEV-II standards.

Table ES-2 provides our estimates of the per vehicle cost for heavy-duty gasoline vehicles and engines. The near-term cost estimates are for the first years that vehicles meeting the standards are sold, prior to cost reductions due to lower productions costs and the retirement of fixed costs. The long-term projections take these cost reductions into account. In the absence of changes to gasoline specifications and with no decrease in fuel economy expected, we do not expect any increase in vehicle operating costs.

Table ES-2. Projected Incremental System Cost and Life Cycle Operating Cost for Heavy-Duty Gasoline Vehicles (Net Present Values in the year of sale, 1999 dollars)

Vehicle Class	Model Year	Incremental System Cost	Life-cycle Operating Cost
Heavy-Duty Gasoline	near term	\$198	\$0
	long term	\$167	\$0

Economic Impact: Fuel Sulfur Requirements

We estimate that the overall net cost associated with producing and distributing 15 ppm diesel fuel, when those costs are allocated to all gallons of highway diesel fuel, will be approximately 5.0 cents per gallon in the long term, or an annual cost of roughly \$2.2 billion per year once the program is fully effective starting in 2010. During the initial years under temporary compliance option, the overall net cost is projected to be 4.5 cents per gallon, or an annual cost of roughly \$1.7 billion per year.

This cost consists of a number of components associated with refining and distributing the new fuel. The majority of the cost is related to refining. From 2006-2010, refining costs are estimated to be approximately 3.3 cents per gallon of highway diesel fuel, increasing to 4.3 cents per gallon once the program is fully in place. In annual terms, the 2006-2010 refining costs are expected to be about \$1.4 billion per year, increasing to about \$1.8 billion in 2010. These figures include the cost of producing slightly more volume of diesel fuel because: 1) desulfurization decreases the energy density of the fuel and 2) slightly more highway diesel fuel is expected to be downgraded to nonroad diesel fuel in the distribution system.

A small cost of 0.2 cents per gallon is associated with an anticipated increase in the use of additives to maintain fuel lubricity. Also, distribution costs are projected to increase by 1.0 cents per gallon during the initial years under the temporary compliance option, including the cost of distributing slightly greater volumes of fuel. Together, these two cost components only amount to about \$0.5 billion per year beginning in 2006. These costs drop to only about \$0.3 billion in 2011 when the temporary compliance option and hardship provisions are over.

Operation with 15 parts per million sulfur diesel fuel is expected to reduce average vehicle maintenance costs by approximately 1 cent on a per gallon basis. Beginning in 2011, this reduction in maintenance costs will total roughly \$400 million per year.

Economic Impact: Aggregate Costs

Using current data for the size and characteristics of the heavy-duty vehicle fleet and making projections for the future, the diesel per-engine, gasoline per-vehicle, and per-gallon fuel costs described above can be used to estimate the total cost to the nation for the emission standards in any year. Figure ES-1 portrays the results of these projections.

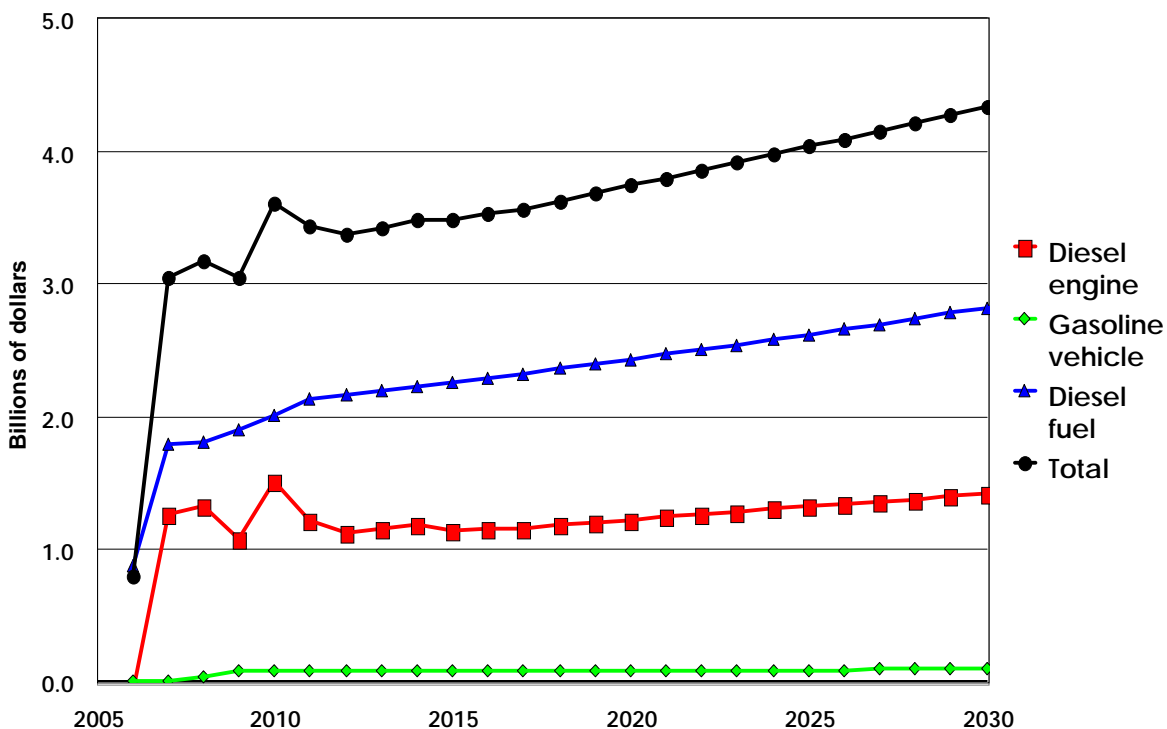


Figure ES-1. Total Annualized Costs

As can be seen from the figure, the annual costs start out at less than 1.0 billion dollars in year 2006 and increase during the initial years to about \$3.6 billion in 2010. Thereafter, total annualized costs are projected to continue increasing due to the effects of projected growth in engine sales and fuel consumption.

Future consumption of 15 parts per million diesel fuel may be influenced by a potential influx of diesel-powered cars and light trucks into the light-duty fleet. The possibility exists that diesels will become more prevalent in the car and light-duty truck fleet, since automotive companies have announced their desire to increase their sales of diesel cars and light trucks. A sensitivity analysis of diesel penetration into the light-duty vehicle fleet results in the expectation that the effect of increased penetration of diesels in the light-duty fleet will likely have little or no impact on the aggregate costs estimated for the standards being finalized in today's action.

Cost-Effectiveness

We have calculated the cost-effectiveness of our diesel engine/gasoline vehicle/diesel sulfur standards based on two different approaches. The first considers the net present value of all costs incurred and emission reductions generated over the life of a single vehicle meeting our standards. This per-vehicle approach focuses on the cost-effectiveness of the program from the point of view of the vehicles and engines which will be used to meet the new requirements. However, the per-vehicle approach does not capture all of the costs or emission reductions from our diesel engine/gasoline vehicle/diesel sulfur program since it does not account for the use of 15 parts per million diesel fuel in current diesel engines. Therefore, we have also calculated a 30-year net present value cost-effectiveness using the net present value of costs and emission reductions for all in-use vehicles over a 30-year time frame. The baseline or point of comparison for this evaluation is the previous set of engine, vehicle, and diesel sulfur standards (in other words, the applicable 2006 model year standards).

The cost of complying with the new standards will decline over time as manufacturing costs are reduced and amortized capital investments are recovered. To show the effect of declining cost in the per-vehicle cost-effectiveness analysis, we have developed both near term and long term cost-effectiveness values. More specifically, these correspond to vehicles sold in years one and six of the vehicle and fuel programs.

The 30-year net present value approach to calculating the cost-effectiveness of our program involves the net present value of all nationwide emission reductions and costs for a 30 year period beginning with the start of the diesel fuel sulfur program and introduction of model year 2007 vehicles and engines in year 2006. This 30-year timeframe captures both the early period of the program when very few vehicles that meet our standards will be in the fleet, and the later period when essentially all vehicles in the fleet will meet the new standards. We have

calculated the 30-year net present value cost-effectiveness using the net present value of the nationwide emission reductions and costs for each calendar year.

Our per-vehicle and 30-year net present value cost-effectiveness values are given in the following tables. The tables summarize the net present value lifetime costs, NMHC + NO_x and PM emission reductions, and resulting cost-effectiveness results for our diesel engine/gasoline vehicle/diesel sulfur standards using sales weighted averages of the costs (both near term and long term) and emission reductions of the various vehicle and engine classes affected for the two different approaches. Diesel fuel costs applicable to diesel engines have been divided equally between the adsorber and trap, since 15 parts per million diesel fuel is intended to enable all technologies to meet our standards. In addition, since the trap produces reductions in both PM and hydrocarbons, we have divided the total trap costs equally between compliance with the PM standard and compliance with the NMHC standard.

The tables also display cost-effectiveness values based on two approaches to account for the reductions in SO₂ emissions associated with the reduction in diesel fuel sulfur. While these reductions are not central to the program and are therefore not displayed with their own cost-effectiveness, they do represent real emission reductions due to our program. The first set of cost-effectiveness numbers in the tables simply ignores these reductions and bases the cost-effectiveness on only the NO_x, NMHC, and PM emission reductions from our program. The second set accounts for these ancillary reductions by crediting some of the cost of the program to SO₂. The amount of cost allocated to SO₂ is based on the cost-effectiveness of SO₂ emission reductions that could be obtained from alternative, potential future EPA programs. The SO₂ credit was applied only to the PM calculation, since SO₂ reductions are primarily a means to reduce ambient PM concentrations.

Table ES-3. Per-Engine^A Cost Effectiveness of the Standards for 2007 and Later MY Vehicles

Pollutants	Discounted lifetime vehicle & fuel costs	Discounted lifetime emission reductions (tons)	Discounted lifetime cost effectiveness per ton	Discounted lifetime cost effectiveness per ton with SO₂ credit^B
<u>Near-term costs</u>				
NO _x + NMHC	\$1937	0.8421	\$2,300	\$2,300
PM	\$1055	0.0672	\$15,697	\$9,058
<u>Long-term costs</u>				
NO _x + NMHC	\$1346	0.8421	\$1,599	\$1,599
PM	\$755	0.0672	\$11,243	\$4,604

^A As described above, per-engine cost effectiveness does not include any costs or benefits from the existing, pre-control, fleet of vehicles that would use the 15 parts per million diesel fuel.

^B \$446 credited to SO₂ (at \$4800/ton) for PM cost effectiveness

Table ES-4. 30-year Net Present Value^A Cost Effectiveness of the Standards

	30-year n.p.v. engine, vehicle, & fuel costs	30-year n.p.v. reduction (tons)	30-year n.p.v. cost effectiveness per ton	30-year n.p.v. cost effectiveness per ton with SO₂ credit^B
NO _x + NMHC	\$34.7 billion	16.2 million	\$2,137	\$2,137
PM	\$10.2 billion	0.8 million	\$13,598	\$4,383

^A This cost effectiveness methodology reflects the total fuel costs incurred in the early years of the program when the fleet is transitioning from pre-control to post-control diesel vehicles. In 2007 <10% of highway diesel fuel is anticipated to be consumed by 2007 MY vehicles. By 2012 this increases to >50% for 2007 and later MY vehicles.

^B \$6.9 billion credited to SO₂ (at \$4800/ton).

Cost-Benefit Analysis

We also made an assessment of the monetary value of the health and general welfare benefits that are expected from the HD Engine/Diesel Fuel rule in 2030. We estimate that this

rule would, in the long term, result in substantial benefits, such as the yearly avoidance of: approximately 8,300 premature deaths, approximately 5,500 cases of chronic bronchitis, roughly 361,400 asthma attacks, and significant numbers of hospital visits, lost work days, and multiple respiratory ailments (including those that affect children). Our standards will also produce welfare benefits related to the reduction of agricultural crop damage, impacts on forest productivity, visibility, and nitrogen deposition in rivers and lakes.

Total monetized benefits of the HD Engine/Diesel Fuel rule in 2030 are expected to be approximately \$70.4 billion. Total monetized benefits, however, are driven primarily by the value placed on the reductions in premature deaths. In the primary estimate, these represent close to 89 percent of total monetized benefits. We estimate the monetary benefit of reducing premature mortality risk using the “value of statistical lives saved” (VSL) approach, even though the actual valuation is of small changes in mortality risk experienced by a large number of people. Since the publication of the Tier 2/Gasoline Sulfur standards earlier this year, EPA has obtained additional advice from its Science Advisory Board (SAB) on the proper characterization of this value and alternatives to EPA’s primary estimate of mortality benefits. Following the advice of the SAB, EPA currently uses the VSL approach in calculating the primary estimate of mortality benefits, because the method reflects the direct application of what EPA and the SAB consider to be the most reasonable estimates for valuation of premature mortality available in the current economics literature.

However, the economics literature concerning the appropriate method for valuing reductions in premature mortality risk is still developing. There is general agreement that the value to an individual of a reduction in mortality risk tends to vary based on several factors, including the age of the individual, the type of risk, the level of control the individual has over the risk, the individual’s attitudes towards risk, and the health status of the individual. While the limited empirical basis for adjusting the VSL used by EPA for many of these factors does not meet the SAB’s standards of reliability at this time, a thorough discussion of these factors is contained in the benefits TSD for this RIA (Abt Associates, 2000). Age in particular may be an important difference between populations affected by air pollution mortality risks and populations affected by workplace risks. Premature mortality risks from air pollution tend to affect the very old more than the working age population. As such, any adjustments to VSL for age differences may have a large impact on total benefits. EPA recognizes the need for further research to improve estimates of the value of premature mortality risk reduction, including potential adjustments to VSL for age and other factors mentioned above.

Based on recent advice from the SAB, our benefits estimates account for expected growth in real income. Economic theory argues that a person’s willingness to pay for most goods (such as environmental protection) will increase as real incomes increase. There is substantial empirical evidence in the economics literature for this idea, although there is uncertainty about its exact value. Based on a review of the available literature, we adjust the valuation of human

health benefits and visibility improvements upward to account for projected growth in real U.S. income to 2030.

As summarized in Table ES-5, our primary estimate of monetary benefits realized in 2030 will be approximately \$70.4 billion dollars (\$1999), including an adjustment for growth in real income as described above. Comparing this estimate of the economic benefits with the adjusted cost estimate indicates that in 2030 the net economic benefits of the HD Engine/Diesel Fuel rule to society are approximately \$66.2 billion dollars (\$1999). Due to the uncertainties associated with this estimate of net benefits, it should be considered along with other components of this RIA, such as: reductions in adverse health and environmental outcomes, total cost, cost-effectiveness, and other benefits and costs that could not be monetized.

Table ES-5. 2030 Annual Monetized Costs, Benefits, and Net Benefits for the Final HD Engine/Diesel Fuel Rule^A

	Billions of 1999\$
Annual compliance costs	\$4.2
Monetized PM-related benefits ^B	\$69.0 + B_{PM}
Monetized Ozone-related benefits ^{B,C}	\$1.4 + B_{Ozone}
NMHC-related benefits	not monetized (B_{NMHC})
CO-related benefits	not monetized (B_{CO})
Total annual benefits	\$70.4 + B_{PM} + B_{Ozone} + B_{NMHC} + B_{CO}
Monetized net benefits ^D	\$66.2 + B

^A For this section, all costs and benefits are rounded to the nearest 100 million. Thus, figures presented in this chapter may not exactly equal benefit and cost numbers presented in earlier sections of the chapter.

^B Not all possible benefits or disbenefits are quantified and monetized in this analysis. Potential benefit categories that have not been quantified and monetized are listed in Table VII-1. Unmonetized PM- and ozone-related benefits are indicated by B_{PM} . And B_{Ozone} , respectively.

^C Ozone-related benefits are only calculated for the Eastern U.S. due to unavailability of reliable modeled ozone concentrations in the Western U.S. This results in an underestimate of national ozone-related benefits. See US EPA (2000a) for a detailed discussion of the UAM-V ozone model and model performance issues.

^D B is equal to the sum of all unmonetized benefits, including those associated with PM, ozone, CO, and NMHC.

Table ES-6 shows the impact of alternative assumptions about key inputs to the benefits analysis, including the concentration-response function relating particulate matter and premature mortality and the dollar value of reductions in the risk of premature mortality. These calculations are based on specific, plausible alternatives to the inputs used in deriving our primary estimate in Table ES-5. See Chapter VII of the RIA for a complete discussion of these and other important alternative calculations and their associated uncertainties.

**Table ES-6. Key Alternative Benefits Calculations
for the HD Engine/Diesel Fuel Rule in 2030^A**

Description of Alternative		Avoided Incidences	Impact on Primary Benefits Estimate Adjusted for Growth in Real Income (billion 1999\$)
Alternative Concentration-Response Functions for PM-related Premature Mortality			
1	Krewski/ACS Study Regional Adjustment Model ^B	9,400	+\$7.4 (+11%)
2	Pope/ACS Study ^C	9,900	+12.8 (+18%)
3	Krewski/Harvard Six-city Study ^D	24,200	+\$118.5 (+169%)
Alternative Methods for Valuing Reductions in Incidences of PM-related Premature Mortality			
Value of avoided premature mortality incidences based on age-specific VSL. ^E	Jones-Lee (1989)	8,300	-\$28.5 (-41%)
	Jones-Lee (1993)	8,300	-\$6.8 (-10%)

^A Please refer to Section 7.F of the RIA for complete information about the estimates in this table.

^B This C-R function is included as a reasonable specification to explore the impact of adjustments for broad regional correlations, which have been identified as important factors in correctly specifying the PM mortality C-R function..

^C The Pope et al. C-R function was used to estimate reductions in premature mortality for the Tier 2/Gasoline Sulfur benefits analysis. It is included here to provide a comparable estimate for the HD Engine/Diesel Fuel rule.

^D The Krewski et al. "Harvard Six-cities Study" estimate is included because the Harvard Six-cities Study featured improved exposure estimates, a slightly broader study population (adults aged 25 and older), and a follow-up period nearly twice as long as that of Pope, et al. and as such provides a reasonable alternative to the primary estimate.

^E Jones-Lee (1989) provides an estimate of age-adjusted VSL based on a finding that older people place a much lower value on mortality risk reductions than middle-age people. Jones-Lee (1993) provides an estimate of age-adjusted VSL based on a finding that older people value mortality risk reductions only somewhat less than middle-aged people.

Regulatory Flexibility Act

Our Regulatory Flexibility Analysis evaluates the impacts of the heavy-duty engine standards and diesel fuel sulfur standards on small businesses. Prior to issuing our proposal we analyzed the potential impacts of our program on small businesses. We convened a Small Business Advocacy Review Panel, as required under the Regulatory Flexibility Act (RFA) as amended by the Small Business Regulatory Enforcement Fairness Act of 1996 (SBREFA). The small business provisions of today's action reflect revisions to the proposed program based upon updated analysis as well as comments heard at the public hearings on the rulemaking and those submitted in writing during the public comment period. The RFA requires us to determine, to the extent feasible, our rule's economic impact on small entities, explore regulatory options for

reducing any significant economic impact on a substantial number of such entities, and explain our ultimate choice of regulatory approach.

In developing this rule, we concluded that the heavy-duty engine and diesel fuel sulfur standards would likely have a significant impact on a substantial number of small entities. We identified several categories of small entities associated with diesel fuel production or distribution. To our knowledge, no manufacturers of heavy-duty engines meet the Small Business Administration definition of a small business. We have determined that the only small entities that may be significantly affected by today's rule are small refiners, since they will have to invest in desulfurization technology to produce low sulfur highway diesel fuel. We quantified the economic impacts on the identified small entities. We determined the refinery costs for average size refineries and small refiners to produce low sulfur diesel fuel. We also estimated diesel distribution costs for the entire distribution system, including pipeline and tank wagon deliveries.

For today's action, we have structured a selection of temporary flexibilities for qualifying small refiners, both domestic and foreign. Generally, we structured these provisions to address small refiner hardship while achieving air quality benefits expeditiously and ensuring that the reductions needed in diesel sulfur coincide with the introduction of 2007 model year diesel vehicles.

All refiners producing highway diesel fuel are able to take a advantage of the temporary compliance option offered in the final regulations. Diesel producers that also market gasoline in the GPA may receive additional flexibility under today's rule. Refiners that seek and are granted small refiner status may choose from the following three options under the diesel sulfur program. These three options have evolved from concepts on which we requested and received comment in the proposal.

500 ppm Option. A small refiner may continue to produce and sell diesel fuel meeting the current 500 ppm sulfur standard for four additional years, until June 1, 2010, provided that it reasonably ensures the existence of sufficient volumes of 15 ppm fuel in the marketing area(s) that it serves.

Small Refiner Credit Option. A small refiner that chooses to produce 15 ppm fuel prior to June 1, 2010 may generate and sell credits under the broader temporary compliance option. Since a small refiner has no requirement to produce 15 ppm fuel under this option, any fuel it produced at or below 15 ppm sulfur will qualify for generating credits.

Diesel/Gasoline Compliance Date Option. For small refiners that are also subject to the Tier 2/Gasoline sulfur program (40 CFR Part 80), the refiner may choose to extend by

three years the duration of its applicable interim gasoline standards, provided that it also produces all its highway diesel fuel at 15 ppm sulfur beginning June 1, 2006.

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List of Acronyms

$\mu\text{g}/\text{m}^3$	micrograms per cubic meter
A/F	air to fuel ratio
ANPRM	Advance Notice of Proposed Rulemaking
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
bbbl	barrel
BTU	British Thermal Unit
CAA or the Act	Clean Air Act
CARB	California Air Resources Board
CASAC	Clean Air Scientific Advisory Committee
CMB	chemical mass balance
CNMI	Commonwealth of Northern Mariana Islands
CO	carbon monoxide
CSMAs	consolidated metropolitan statistical areas
DECSE	Diesel Emission Control Sulfur Effects
DOC	diesel oxidation catalyst
EGR	exhaust gas recirculation
EHC	electrically heated catalyst
EIA	Energy Information Administration
EPA or the Agency	U.S. Environmental Protection Agency
FCC	fluidized catalytic cracker
FTP	federal test procedure
g/bhp-hr	grams per brake-horsepower-hour
GVWR	gross vehicle weight rating
HC	hydrocarbon
HD-FTP	heavy-duty federal test procedure
HDE	heavy-duty engine
HDV	heavy-duty vehicle
HLDT	heavy light-duty truck
I/M	inspection/maintenance

IARC	International Agency for Research on Cancer
IRFA	initial regulatory flexibility analysis
LCO	light cycle oil
LDT	light-duty truck
LDV	light-duty vehicle
LEV	low emission vehicle
LLDT	light light-duty truck
LPG	liquid petroleum gas
MDPV	medium-duty passenger vehicle
MECA	Manufacturers of Emission Controls Association
MECA	Manufacturers of Emission Controls Association
MSAs	metropolitan statistical areas
MSCF	thousand standard cubic feet
MY	model year
NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System
NCPs	non-conformance penalties
NMHC	non-methane hydrocarbons
NMOG	non-methane organic gases
NO ₂	nitrogen dioxide
NO _x	oxides of nitrogen
NPC	National Petroleum Council
NPRA	National Petrochemical & Refiners Association
NPRM	Notice of Proposed Rulemaking
NPV	net present value
NRC	National Research Council
NSR	New Source Review
NSWS	National Surface Water Survey
NTE	not-to-exceed
OAQPS	Office of Air Quality Planning and Standards
OBD	on-board diagnostics
OMB	Office of Management and Budget

List of Acronyms

OMS	Office of Mobile Sources
PADD	Petroleum Administrative Districts for Defense
Pd	palladium
PM	particulate matter
POM	polycyclic organic matter
ppm	part per million
Pt	platinum
R&D	research and development
RFA	Regulatory Flexibility Act
RfC	reference concentration
Rh	rhodium
RIA	Regulatory Impact Analysis
ROI	return on investment
SBA	U.S. Small Business Administration
SBARP or the Panel	Small Business Advocacy Review Panel
SBREFA	Small Business Regulatory Enforcement Fairness Act
SCR	selective catalytic reduction
SER	Small Entity Representative
SFTP	supplemental federal test procedure
SIC	Standard Industrial Classification
SIGMA	Society of Independent Gasoline Marketers of America
SIP	State Implementation Plan
SO ₂	sulfur dioxide
SOF	soluble organic fraction
SO _x	oxides of sulfur
TAC	toxic air contaminant
TOG	total organic gases
TW	test weight
UDDS	urban dynamometer driving schedule
ULEV	ultra-low emission vehicles
VMT	vehicle miles traveled
VOC	volatile organic compound

Chapter I: Introduction

We prepared this Regulatory Impact Analysis (RIA) for our final rulemaking (FRM) on Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements. The purpose of this document is to present our estimates of the likely costs, benefits, and industry impacts associated with the implementation of the final heavy-duty engine and vehicle standards and the diesel sulfur requirements. Throughout this RIA we have referenced a number of technical documents published by the Society of Automotive Engineers (SAE). Information on how to obtain copies of these technical documents is available in the docket for this rulemaking.^a

This chapter provides an overview of the final rule. Subsequent chapters present the following information:

- **Chapter II** presents the health and welfare concerns associated with heavy-duty vehicle emissions, and the expected emissions reductions resulting from the new standards.
- **Chapter III** examines the engine and vehicle changes needed to meet the heavy-duty emission standards and the feasibility of these changes under the implementation schedule. It also presents the basis for the need for diesel fuel sulfur levels of 15 parts per million or less.
- **Chapter IV** examines the refinery and fuel distribution system changes needed to meet the low sulfur highway diesel fuel requirement and the feasibility of these changes under the implementation schedule.
- **Chapter V** estimates the economic impact of the engine/vehicle and fuels standards in per-vehicle and per-gallon terms, and in the aggregate.
- **Chapter VI** discusses the cost-effectiveness of the program in achieving emission reductions.
- **Chapter VII** discusses the cost-benefit analysis of the program.

^a EPA Memorandum “Obtaining Society of Automotive Engineers (SAE) Technical Papers”, William Charmley, copy available in EPA Air Docket A-99-06.

- **Chapter VIII** presents the Regulatory Flexibility Analysis (RFA) for this FRM. This analysis evaluates the impacts of the heavy-duty engine and vehicle standards and the diesel sulfur requirements on small businesses.
- **Chapter IX** analyzes the issues surrounding how the engine and fuel standards should be applied in Alaska and U.S. territories.
- **Appendix A** describes current regulatory requirements that affect diesel sulfur content and explains our bases for controlling diesel sulfur under Section 211(c) of the Clean Air Act.
- **Appendix B** contains a table of vehicle miles traveled by heavy-duty diesel engine class.

The final rule implements the second of two phases of a comprehensive nationwide program for controlling emissions from heavy-duty engines (HDEs) and vehicles. It builds upon the phase 1 program we recently finalized (65 FR 59896, October 6, 2000). That action reviewed and confirmed the 2004 model year emission standards set in 1997 (62 FR 54693, October 21, 1997), finalized stringent new emission standards for gasoline-fueled heavy-duty vehicles (HDVs), and finalized other changes to the heavy-duty program, including provisions to ensure in-use emissions control.

This second phase of the program looks beyond 2004, based on the use of high-efficiency exhaust emission control devices and the consideration of the vehicle and its fuel as a single system. In developing the final rule, we took into consideration comments received in response to a notice of proposed rulemaking (NPRM) published in June of this year (65 FR 35430, June 2, 2000), and comments we received in response to our discussion of future standards in the heavy-duty 2004 standards rulemaking.

There are two basic parts to the final rule: (1) new exhaust emission standards for heavy-duty highway engines and vehicles, and (2) new quality standards for highway diesel fuel. The systems approach of combining the engine and fuel standards into a single program is critical to the success of our overall efforts to reduce emissions, because the emission standards would not be feasible without the fuel change. This is because the emission standards are expected to result in the use of high-efficiency exhaust emission control devices that would be damaged by sulfur in the fuel. This final rule, by providing extremely low sulfur diesel fuel, will also enable cleaner diesel passenger vehicles and light-duty trucks. This is because the same pool of highway diesel fuel also services these light-duty diesel vehicles, and these vehicles can employ technologies similar to the high-efficiency heavy-duty exhaust emission control technologies that will be enabled by the fuel change. We believe these technologies are needed for diesel vehicles to comply with our recently adopted Tier 2 emissions standards for light-duty highway vehicles (65 FR 6698, February 10, 2000).

We believe that this systems approach is a comprehensive way to enable promising new technologies for clean diesel affecting all sizes of highway diesel engines and, eventually, diesel engines used in nonroad applications too. The fuel change, in addition to enabling new technologies, will also produce emissions and maintenance benefits in the existing fleet of highway diesel vehicles. These benefits include reduced sulfate and sulfur oxides emissions, reduced engine wear and less frequent oil changes, and longer-lasting exhaust gas recirculation (EGR) components on engines equipped with EGR. Heavy-duty gasoline vehicles will also be expected to reach cleaner levels due to the transfer of recent technology developments for light-duty applications, and the recent action taken to reduce sulfur in gasoline as part of the Tier 2 rule.

The basic elements of the final rule are outlined below. We are finalizing a PM emissions standard for new heavy-duty engines of 0.01 grams per brake-horsepower-hour (g/bhp-hr), to take full effect for diesels in the 2007 model year. We are also finalizing standards for NO_x and NMHC of 0.20 g/bhp-hr and 0.14 g/bhp-hr, respectively. These NO_x and NMHC standards will be phased in together between 2007 and 2010, for diesel engines. The phase-in will be on a percent-of-sales basis: 50 percent from 2007 to 2009 and 100 percent in 2010. Gasoline engines will be subject to these standards based on a phase-in requiring 50 percent compliance in the 2008 model year and 100 percent compliance in the 2009 model year. In addition, we are finalizing our proposal to include turbocharged diesels in the existing crankcase emissions prohibition, effective in 2007, with some revisions that allow some level of crankcase emissions to be discharged as long as the sum total of crankcase and exhaust emissions remains below the applicable standard.

Standards for complete HDVs will be implemented on the same schedule as for gasoline engine standards. For certification of complete vehicles between 8500 and 10,000 pounds gross vehicle weight rating (GVWR), the standards are 0.2 grams per mile (g/mi) for NO_x, 0.02 g/mi for PM, 0.195 g/mi for NMHC, and 0.016 g/mi for formaldehyde.^b For vehicles between 10,000 and 14,000 pounds, the standards are 0.4 g/mi for NO_x, 0.02 g/mi for PM, and 0.230 g/mi for NMHC, and 0.021 g/mi for formaldehyde. These standards levels are roughly comparable to the engine-based standards in these size ranges. Note that these standards will not apply to vehicles above 8500 pounds that we classify as medium-duty passenger vehicles as part of our Tier 2 program.

We are adopting new evaporative emissions standards for heavy-duty engines and vehicles, effective on the same schedule as the gasoline engine and vehicle exhaust emission standards. The new standards for 8500 to 14,000 pound vehicles are 1.4 and 1.75 grams per test for the 3-day diurnal and supplemental 2-day diurnal tests, respectively. Standards levels of 1.9

^b Vehicle weight ratings in this rule refer to GVWR (the curb weight of the vehicle plus its maximum recommended load of passengers and cargo) unless noted otherwise.

and 2.3 grams per test will apply for vehicles over 14,000 pounds. These standards represent more than a 50 percent reduction in the numerical standards as they exist today.

Finally, this rule specifies that, beginning September 1, 2006, diesel fuel sold for use in model year 2007 and later highway vehicles must be limited in sulfur content to 15 parts per million (ppm). This sulfur standard is based on our assessment of the impact of sulfur on advanced exhaust emission control technologies, and a corresponding assessment of the feasibility of low sulfur fuel production and distribution.

The new program includes a combination of flexibilities available to refiners to ensure a smooth transition to low sulfur highway diesel fuel. First, refiners can take advantage of a temporary compliance option which includes a banking and trading component. Under this voluntary option, a restricted amount of highway diesel fuel may continue to be produced at the existing 500 ppm sulfur maximum standard. At the end of the transition period all highway diesel fuel must meet the 15 ppm sulfur standard. Second, we are providing additional flexibilities for small refiners to minimize their economic burden in complying with the 15 ppm sulfur standard. Third, we are including a provisions for refiners located in the Geographic Phase-in Area (GPA) as defined in the Tier 2 program which will allow them to stagger their gasoline and diesel investments. Finally, we are adopting a general hardship provision for which any refiner may apply on a case-by-case basis under certain conditions.

With minor exceptions, existing compliance provisions for ensuring diesel fuel quality that have been in effect since 1993 remain unchanged (55 FR 34120, August 21, 1990). Additional compliance provisions have been established primarily during the first four years of the program to verify refiners' compliance with the temporary compliance option and various hardship provisions, to ensure the two grades of highway diesel fuel remain segregated, and to prevent misfueling of model year 2007 and later diesel vehicles.

Chapter II: Health and Welfare Concerns and Emissions Benefits

This chapter describes the public health and welfare concerns associated with the pollutants emitted by heavy-duty vehicles, and the emission reductions that are expected to occur as a result of today's action. Specifically, we present information on the ambient air pollution situation that is likely to exist without this rule between 2007 and 2030 for ambient pollutants of concern (e.g., ozone, particulate matter). In addition, this chapter presents information on the expected emission reductions based on our projected national heavy-duty vehicle emissions with and without the new standards for nitrogen oxides (NO_x), non-methane hydrocarbons (NMHC), particulate matter (PM), sulfur dioxide (SO_x), carbon monoxide (CO), and air toxics.

A. Health and Welfare Concerns

When revising emissions standards for heavy-duty vehicles, the Agency considers the effects of air pollutants emitted from heavy-duty vehicles on public health and welfare.¹ As discussed in more detail below, the outdoor, or ambient, air quality in many areas of the country is expected to violate federal health-based ambient air quality standards for ground level ozone and particulate matter during the time when this rule will take effect. In addition, some studies have found public health and welfare effects from ozone and PM at concentrations that do not constitute a violation of their respective NAAQS. Other studies have associated diesel exhaust with cancer and noncancer health effects. Of particular concern is human epidemiological evidence linking diesel exhaust to an increased risk of lung cancer. Emissions from heavy-duty vehicles also contribute to a variety of environmental and public welfare effects such as impairment of visibility/ regional haze, acid deposition, eutrophication/ nitrification, and POM deposition. As described in more detail throughout this chapter, the standards finalized in this rule will result in a significant improvement in ambient air quality and public health and welfare.

1. Health and Welfare Concerns Raised During Public Hearings

Throughout the five public hearings held around the country on the heavy-duty engine and diesel fuel rule, the Agency received strong public support at each venue for increasing the stringency of heavy-duty truck and bus emission standards, and for further controls on sulfur in diesel fuel, in order to enable the necessary exhaust emission control. Public officials and representatives of environmental, public health, or community-based organizations testified regularly about the link between public health ailments, such as asthma and lung cancer, and air pollution caused by diesel exhaust and particulate matter. A common theme revolved around the

notion that since asthma is an incurable disease, it was of utmost importance to help reduce the severity and frequency of attacks by reducing environmental triggers such as ozone, particulate matter and diesel exhaust. Many testifiers expressed a strong sentiment that the public and the auto industry have done their fair share to clean up cars and keep them clean through regular inspections and maintenance, and it was time for the diesel truck industry to do the same.

In different ways, many noted that the impact of diesel soot is compounded by the fact that it is discharged at street level where people live and breathe. A common complaint was the close proximity of bus depots, transfer terminals, and heavily-trafficked roadways to homes and apartment buildings, and in particular, to hospitals, playgrounds, and schools. Cyclists described the stinging eyes and choking caused by breathing fumes from buses and trucks along city streets, especially when trucks accelerated after stopping at an intersection. Two testifiers cited to health studies that they said reported an association between those living in homes located near heavily-trafficked streets and increased incidences of childhood asthma and leukemia.

By far the most poignant testimony was about how air pollution has impaired the health and well-being of children. As our recent reviews of the NAAQS have documented, we heard concerns expressed by citizens that childhood asthma accounts for 10.1 million missed school days in the United States each year, and that asthma is the leading cause of hospitalizations in New York City for children aged 0-14. At times, parents and their children testified together. Kyle Damitz, accompanied by his mother, entered the following testimony:

I have come here today to tell you how our bad air affects kids like me with asthma. . . . During these ozone days, I will almost always have an asthma attack if I go outside. On good days, I take two pills in the morning and three pills at bedtime. I do an IV treatment every two weeks. On a bad asthma day, I take four pills in the morning, more at lunch, and again, more at bedtime. . . . I came here today to . . . ask you to help make breathing for kids with asthma easier. By making the air cleaner, you are giving asthmatics a chance to breathe easier. If our air was cleaner, I would be able to take less medicine, be able to play outside more. If you make our air cleaner, I will be able to live longer.

Many testifiers took the Agency to task for not acting sooner on heavy-duty vehicles. Reacting to industry testimony requesting additional time to comply with the standards, testifiers representing their constituents, their communities, environmental organizations, or themselves, expressed the simple desire to be healthy as soon as possible. Some compared the annual human cost of air pollution – quantified by thousands of hospitalizations, emergency room and doctors visits, asthma attacks -- with per vehicle cost of \$1,600, and stated their belief that the

regulations are cost effective. Others suggested that several billion dollars spent on improving the environmental performance of trucks and buses was reasonable in light of the petroleum industry's multi-billion dollar profits in the first quarter of 2000.

Major industries represented during these public hearings were the heavy-duty vehicle engine manufacturers, the oil industry, and the commercial truckers. While each had a different perspective, most supported the underlying intent of this rule to improve public health and welfare, and some also supported the specific requirements as proposed. For those who objected to the proposal, the main thrust of their concerns related to the stringency and public health necessity of the new standards and the diesel fuel sulfur requirement. Largely in their written comments, these industries raised questions about the need for additional reductions in order to meet existing ozone and PM national ambient air quality standards and took exception with the Agency's characterization of diesel exhaust as a human carcinogen at environmental levels of exposure. Some industry commenters also challenged the Agency's reliance on public welfare and environmental effects such as visibility impairment and eutrophication of water bodies because the Agency had insufficiently quantified the benefits that would result from new standards on heavy-duty vehicles and diesel fuel.

The following subsections present the available information on the air pollution situation that is likely to exist without this rule for each ambient pollutant. We also present information on the improvement that is expected to result from this rule. The Agency received a significant number of comments on this section during the public hearings and in written comments from interested parties. Where appropriate, comments are addressed in this section, but the majority are addressed only in the Response to Comment document that accompanies this preamble. Interested parties should refer to the Response to Comment document for the Agency's response to their specific comments.

2. Ozone

This section reviews health and welfare effects of ozone and describes the air quality information that forms the basis of our belief that ozone concentrations in many areas across the country face a significant risk of exceeding the ozone standard between 2007 and 2030. Information on air quality was gathered from a variety of sources, including monitored ozone concentrations from 1997-1999, air quality modeling forecasts conducted for this rulemaking, ozone modeling and information from states that have recently submitted attainment demonstrations, and other state and local air quality information. Studies have found that ozone concentrations at levels that do not exceed the 1-hour ozone standard are associated with impacts on public health and welfare, and this section also summarizes those health effects and provides some information about the potential for ozone at these moderate levels to exist during the time period when this rule will take effect.

a. Health and Welfare Effects of Ozone and its Precursors

Ground-level ozone, the main ingredient in smog, is formed by complex chemical reactions of VOC and NO_x in the presence of heat and sunlight. Ozone forms readily in the lower atmosphere, usually during hot summer weather. Volatile Organic Compounds are emitted from a variety of sources, including motor vehicles, chemical plants, refineries, factories, consumer and commercial products, and other industrial sources. Volatile organic compounds also are emitted by natural sources such as vegetation. Oxides of Nitrogen are emitted largely from motor vehicles, off-highway equipment, power plants, and other sources of combustion.

The science of ozone formation, transport, and accumulation is complex. Ground-level ozone is produced and destroyed in a cyclical set of chemical reactions involving NO_x, VOC, heat, and sunlight.^a As a result, differences in NO_x and VOC emissions and weather patterns contribute to daily, seasonal, and yearly differences in ozone concentrations and differences from city to city. Many of the chemical reactions that are part of the ozone-forming cycle are sensitive to temperature and sunlight. When ambient temperatures and sunlight levels remain high for several days and the air is relatively stagnant, ozone and its precursors can build up and produce more ozone than typically would occur on a single high temperature day. Further complicating matters, ozone also can be transported into an area from pollution sources found hundreds of miles upwind, resulting in elevated ozone levels even in areas with low VOC or NO_x emissions.

Emissions of NO_x and VOC are precursors to the formation of ozone in the lower atmosphere. For example, relatively small amounts of NO_x enable ozone to form rapidly when VOC levels are relatively high, but ozone production is quickly limited by removal of the NO_x. Under these conditions, NO_x reductions are highly effective in reducing ozone while VOC reductions have little effect. Such conditions are called "NO_x limited." Because the contribution of VOC emissions from biogenic (natural) sources to local ambient ozone concentrations can be significant, even some areas where man-made VOC emissions are relatively low can be NO_x limited.

When NO_x levels are relatively high and VOC levels relatively low, NO_x forms inorganic nitrates but relatively little ozone. Such conditions are called "VOC limited." Under these conditions, VOC reductions are effective in reducing ozone, but NO_x reductions can actually increase local ozone under certain circumstances. Even in VOC limited urban areas, NO_x reductions are not expected to increase ozone levels if the NO_x reductions are sufficiently large. The highest levels of ozone are produced when both VOC and NO_x emissions are present in significant quantities on clear summer days.

^a Carbon monoxide also participates in the production of ozone, albeit at a much slower rate than most VOC and NO_x compounds.

Rural areas are almost always NO_x limited, due to the relatively large amounts of biogenic VOC emissions in such areas. Urban areas can be either VOC or NO_x limited, or a mixture of both, in which ozone levels exhibit moderate sensitivity to changes in either pollutant.

Ozone concentrations in an area also can be lowered by the reaction of nitric oxide with ozone, forming nitrogen dioxide (NO₂); as the air moves downwind and the cycle continues, the NO₂ forms additional ozone. The importance of this reaction depends, in part, on the relative concentrations of NO_x, VOC, and ozone, all of which change with time and location.

Based on a large number of recent studies, EPA has identified several key health effects caused when people are exposed to levels of ozone found today in many areas of the country.^{2, 3} Short-term exposures (1-3 hours) to high ambient ozone concentrations have been linked to increased hospital admissions and emergency room visits for respiratory problems. For example, studies conducted in the northeastern U.S. and Canada show that ozone air pollution is associated with 10-20 percent of all of the summertime respiratory-related hospital admissions. Repeated exposure to ozone can make people more susceptible to respiratory infection and lung inflammation and can aggravate preexisting respiratory diseases, such as asthma. Prolonged (6 to 8 hours), repeated exposure to ozone can cause inflammation of the lung, impairment of lung defense mechanisms, and possibly irreversible changes in lung structure, which over time could lead to premature aging of the lungs and/or chronic respiratory illnesses such as emphysema and chronic bronchitis.

Children and outdoor workers are most at risk from ozone exposure because they typically are active outside, playing and exercising, during the summer when ozone levels are highest. For example, summer camp studies in the eastern U.S. and southeastern Canada have reported significant reductions in lung function in children who are active outdoors. Further, children are more at risk than adults from ozone exposure because their respiratory systems are still developing. Adults who are outdoors and moderately active during the summer months, such as construction workers and other outdoor workers, also are among those most at risk. These individuals, as well as people with respiratory illnesses such as asthma, especially asthmatic children, can experience reduced lung function and increased respiratory symptoms, such as chest pain and cough, when exposed to relatively low ozone levels during prolonged periods of moderate exertion.

Evidence also exists of a possible relationship between daily increases in ozone levels and increases in daily mortality levels. While the magnitude of this relationship is still too uncertain to allow for direct quantification, the full body of evidence indicates the possibility of a positive relationship between ozone exposure and premature mortality.

In addition to human health effects, ozone adversely affects crop yield, vegetation and forest growth, and the durability of materials. Because ground-level ozone interferes with the

ability of a plant to produce and store food, plants become more susceptible to disease, insect attack, harsh weather and other environmental stresses. Ozone causes noticeable foliage damage in many crops, trees, and ornamental plants (i.e., grass, flowers, shrubs, and trees) and causes reduced growth in plants. Studies indicate that current ambient levels of ozone are responsible for damage to forests and ecosystems (including habitat for native animal species). Ozone chemically attacks elastomers (natural rubber and certain synthetic polymers), textile fibers and dyes, and, to a lesser extent, paints. For example, elastomers become brittle and crack, and dyes fade after exposure to ozone.

Volatile organic compound emissions are detrimental not only for their role in forming ozone, but also for their role as air toxics. Some VOCs emitted from motor vehicles are toxic compounds. At elevated concentrations and exposures, human health effects from air toxics can range from respiratory effects to cancer. Other health impacts include neurological, developmental and reproductive effects. The toxicologically significant VOCs emitted in substantial quantities from HDVs are discussed in detail in Section II.A.4 below.

Besides their role as an ozone precursor, NO_x emissions produce a wide variety of health and welfare effects.^{4 5} These problems are caused in part by emissions of nitrogen oxides from motor vehicles. Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infection (such as influenza). NO_x emissions are an important precursor to acid rain and may affect both terrestrial and aquatic ecosystems. Atmospheric deposition of nitrogen leads to excess nutrient enrichment problems (“eutrophication”) in the Chesapeake Bay and several nationally important estuaries along the East and Gulf Coasts. Eutrophication can produce multiple adverse effects on water quality and the aquatic environment, including increased algal blooms, excessive phytoplankton growth, and low or no dissolved oxygen in bottom waters. Eutrophication also reduces sunlight, causing losses in submerged aquatic vegetation critical for healthy estuarine ecosystems. Deposition of nitrogen-containing compounds also affects terrestrial ecosystems. Nitrogen fertilization can alter growth patterns and change the balance of species in an ecosystem. In extreme cases, this process can result in nitrogen saturation when additions of nitrogen to soil over time exceed the capacity of plants and microorganisms to utilize and retain the nitrogen. These environmental impacts are discussed further in Sections II.A.6 and II.A.7.

Elevated levels of nitrates in drinking water pose significant health risks, especially to infants. Studies have shown that a substantial rise in nitrogen levels in surface waters are highly correlated with human-generated inputs of nitrogen in those watersheds.⁶ These nitrogen inputs are dominated by fertilizers and atmospheric deposition. Nitrogen dioxide and airborne nitrate also contribute to pollutant haze, which impairs visibility and can reduce residential property values and the value placed on scenic views.

b. Photochemical Ozone Modeling

In conjunction with this rulemaking, the Agency performed a series of ozone air quality modeling simulations for nearly the entire Eastern U.S covering metropolitan areas from Texas to the Northeast.^b The model simulations were performed for five emissions scenarios: a 2007 baseline projection, a 2020 baseline projection and a 2020 projection with heavy-duty vehicle controls, a 2030 baseline projection, and a 2030 projection with heavy-duty vehicle controls.

The model outputs from the 2007, 2020 and 2030 baselines, combined with current air quality data, were used to identify areas expected to exceed the ozone NAAQS in 2007, 2020 and 2030. These areas became candidates for being determined to be residual exceedance areas which will require additional emission reductions to attain and maintain the ozone NAAQS. The impacts of the heavy-duty vehicle controls were determined by comparing the model results in the future year control runs against the baseline simulations of the same year. This modeling supports the conclusion that there is a broad set of areas with predicted ozone concentrations at or above 0.125 ppm between 2007 and 2030 in the baseline scenarios without additional emission reductions.

The air quality modeling performed for this rule was based upon the same modeling system as was used in the Tier 2 air quality analysis, with the addition of updated inventory estimates for 2007, 2020 and 2030. Consistent with a commitment expressed in the rule proposal, the Agency released the emissions inventory inputs for, and a description of ozone modeling, into the public record (docket number A-99-06), and also onto a website developed expressly for this purpose, on a continuous basis as they were developed. Further discussion of this modeling, including evaluations of model performance relative to predicted future air quality, is provided in the air quality modeling technical support document (TSD).

i. Modeling Methodology, Domains, and Episodes

A variable-grid version of the Urban Airshed Model (UAM-V) was utilized to estimate base and future-year ozone concentrations over the eastern U.S. for the various emissions scenarios. UAM-V simulates the numerous physical and chemical processes involved in the formation, transport, and destruction of ozone. This model is commonly used for purposes of determining attainment/non-attainment as well as estimating the ozone reductions expected to

^b EPA also performed ozone air quality modeling for the western United States but, as described further in the air quality technical support document, model predictions were well below corresponding ambient concentrations. Given that model performance was degraded to the extent that the directional response of the model to controls may be questionable, and considering the performance relative to that for the East and what is typically expected out of such regulation modeling applications, it was determined that the results of western ozone modeling were not relied on for this rule.

occur from a reduction in emitted pollutants. The following sections provide an overview of the ozone modeling completed as part of this rulemaking. More detailed information is included in the air quality modeling TSD, which is located in the docket for this rule.

The eastern modeling domain covered that portion of the U.S. east of west longitude 99 degrees. The model resolution was 36 km over the outer portions of the domain and 12 km in the inner portion of the grids. A modeling study considered the sensitivity of regional modeling strategies to grid resolution (LADCO, 1999). This study showed that the spatial pattern and magnitude of the ozone changes at 4 km in response to emissions reductions were slightly more pronounced, but generally similar to the modeled changes at 12 km in the Lake Michigan area. The Ozone Transport Assessment Group (OTAG)^c modeling application also investigated the effects of grid resolution on national/regional control strategies. The OTAG Final Report concluded that: a) peak simulated ozone is generally higher with more highly resolved grids, b) spatial concentration patterns are comparable between the fine and the coarse grid, and c) NOx reductions produce widespread ozone decreases and occasional limited ozone increases with either the fine or the coarse grid (although the increases tend to be larger in magnitude when finer-scale grids are used). More detail on the effect of grid size upon model results is provided in the response to comments and the TSD for this final rule.

Three multi-day meteorological scenarios during the summer of 1995 were used in the model simulations over the eastern U.S.: 12-24 June, 5-15 July, and 7-21 August. These periods featured ozone exceedances at various times over many areas of the eastern U.S.^d In general, these episodes do not represent extreme ozone events but, instead, are generally representative of ozone levels near local design values. Each of the six emissions scenarios (1996 base year, 2007 baseline, 2020 base, 2020 control, 2030 baseline, 2030 control) were simulated for the three episodes.

ii. Non-emissions Modeling Inputs

The meteorological data required for input into UAM-V (wind, temperature, vertical mixing, etc.) were developed by a separate meteorological model, the Regional Atmospheric Modeling System (RAMS) for the eastern U.S. 1995 episodes. This model provided needed data at every grid cell on an hourly basis. These meteorological modeling results were evaluated

^c The OTAG modeling project is used as a benchmark for this heavy-duty vehicle and low sulfur diesel fuel modeling because it is the most extensive regional ozone modeling application completed to date in terms of days modeled, areas covered, and efforts of the air pollution modeling community to obtain sound model performance.

^d Each modeling episode contains three days for which the modeling results are not considered. These days are simulated to minimize the dependence of the modeling results on uncertain initial conditions.

against observed weather conditions before being input into UAM-V and it was concluded that the model fields were adequate representations of the historical meteorology.

The modeling assumed background pollutant levels at the top and along the periphery of the domain. Additionally, initial conditions were assumed to be relatively clean as well. Given the ramp-up days and the expansive domains, it is expected that these assumptions will not affect the modeling results, except in areas near the boundary (e.g., Dallas-Fort Worth TX). The other non-emission UAM-V inputs (land use, photolysis rates, etc.) were developed using procedures employed in the OTAG regional modeling. The development of model inputs is discussed in greater detail in the Air Quality Technical Support Document, which is available in the docket to this final action on heavy-duty vehicles.

iii. Model Performance Evaluation

The purpose of the Heavy Duty Engine base year modeling was to reproduce the atmospheric processes resulting in the observed ozone concentrations over these domains and episodes. One of the fundamental assumptions in air quality modeling is that a model which adequately replicates observed pollutant concentrations in the base year can be used to support future-year policymaking (i.e., assessing the effects of altering the original emissions state).

As with previous regional photochemical modeling studies, the accuracy of the Heavy Duty Engine base year simulations of historical ozone patterns varies by day and by location over this large modeling domain. From a qualitative standpoint, there appears to be considerable similarity on most days between the observed and simulated ozone patterns. Additionally, where possible to discern, the model appears to follow the day-to-day variations in synoptic-scale ozone fairly closely.

The values of the two primary measures of model performance, mean normalized bias and mean normalized gross error, indicate that the Heavy Duty Engine modeling over the eastern U.S. is generally as good as the grid modeling done to support the Tier 2/Sulfur rulemaking, as shown in Table II.A-1. In turn, the performance of the Tier 2/Sulfur modeling was determined to be as good or better than the detailed OTAG regional modeling, which has served as a relative benchmark for acceptable performance from a regional photochemical grid model.

Table II.A-1. Comparison of eastern U.S. regional model performance statistics between the Tier 2/Sulfur modeling and the Heavy Duty Engine modeling. The units are percentages.

<i>Mean Normalized Bias</i>	<i>Tier 2 June 95</i>	<i>Tier 2 July 95</i>	<i>Tier 2 August 95</i>	<i>HDE June 95</i>	<i>HDE July 95</i>	<i>HDE August 95</i>
Domain	-10	-6	+2	-13	-11	+5
Midwest	-11	-13	+7	-15	-16	+10
Northeast	-17	-9	-9	-20	-11	-15
Southeast	-4	+4	+7	-7	-3	+12
Southwest	+2	+8	+6	+1	+3	+11

<i>Mean Normalized Gross Error</i>	<i>Tier 2 June 95</i>	<i>Tier 2 July 95</i>	<i>Tier 2 August 95</i>	<i>HDE June 95</i>	<i>HDE July 95</i>	<i>HDE August 95</i>
Domain	24	24	23	22	23	24
Midwest	24	26	22	22	24	22
Northeast	27	22	24	27	23	24
Southeast	20	24	22	18	21	25
Southwest	24	27	24	22	24	27

Mean normalized bias is defined as the average difference between model predictions and observations (paired in space and time) normalized by the magnitude of the observations. Mean normalized gross error is defined as the average absolute difference between model predictions and observations, paired in space and time, normalized by the magnitude of the observations. EPA guidance on local ozone attainment demonstration modeling (not the purpose of the Heavy Duty Engine modeling) suggests biases be no greater than 15 percent and errors be no greater than 35 percent.

Model performance statistics for the Heavy Duty Engine base case simulations were calculated for the entire grid and numerous smaller sub-grids. The model performance evaluation consisted solely of comparisons against ambient surface ozone data. There was insufficient data available in terms of ozone precursors or ozone aloft to allow for a more complete assessment of model performance. From a regional perspective, the model generally

underestimated observed ozone values (greater than 60 ppb) for the June and July episodes, but predicted higher than observed amounts for the August episode. Errors average about 22-24 percent. The general tendency of the model, as discussed above, is to underestimate observed ozone concentrations. This tendency should lead to a conservative estimate of future-year air quality need.

c. Results of Photochemical Ozone Modeling

The determination that an area is at risk of exceeding the ozone standard in the future was made for all areas with current design values greater than or equal to 0.125 ppm (or within a 10 percent margin) and with modeling evidence that exceedances will persist into the future. The following sections provide background on methods for analysis of attainment and maintenance. Those interested in greater detail should review the Air Quality Modeling Technical Support Document, which is available in the docket to this rule.

i. Air Quality Design Values

An ozone design value is the concentration that determines whether a monitoring site meets the NAAQS for ozone. Because of the way they are defined, design values are determined based on three consecutive-year monitoring periods. A 1-hour design value is the fourth highest daily maximum 1-hour average ozone concentration measured over a three-year period at a given monitor. The full details of these determinations (including accounting for missing values and other complexities) are given in Appendices H and I of 40 CFR Part 50. As discussed in these appendices, design values are truncated to whole part per billion (ppb). Due to the precision with which the standards are expressed (0.12 parts per million (ppm) for the 1-hour), a violation of the 1-hour standard is defined as a design value greater than or equal to 0.125 ppm.

For a county, the design value is the highest design value from among all the monitors with valid design values within that county. If a county does not contain an ozone monitor, it does not have a design value. For most of our analyses, county design values are consolidated where possible into design values for consolidated metropolitan statistical areas (CMSA) or metropolitan statistical areas (MSA). The design value for a metropolitan area is the highest design value among the included counties. Counties that are not in metropolitan areas are treated separately and are not considered in this analysis. For the purposes of defining the current design value of a given area, the 1997-1999 design values were chosen to provide the most recent set of air quality data for identifying areas likely to have an ozone problem in the future. The 1997-1999 design values are listed in the Air Quality Modeling Technical Support Document, which is available in the docket to this rule.

ii. Method for Projecting Future Exceedances

The exceedance method was used for interpreting the future-year modeling results to determine where there is an appreciable risk of future nonattainment in the 2007, 2020 and 2030 Base and Control Cases. As part of this method, the modeling grid cells are first assigned to individual areas. The daily maximum 1-hour ozone values predicted in grid cells assigned to an area are then checked to identify whether there are any predictions greater than or equal to 0.125 ppm. Areas with current measured violations of the one-hour ozone standard (or within a 10 percent margin), and one or more model-predicted exceedances, are projected to have the potential for a nonattainment problem in the future.

iii. Areas at Risk of Future Exceedances Based on Ozone Predictive Modeling

The Agency conducted ozone modeling based on inventories developed with and without reductions from this rulemaking for three future years: 2007, 2020, and 2030. The year 2007 was chosen because it is the first year of implementation for the new standards adopted in today's action. It is also the year that ten major urban areas with a history of persistent and elevated ozone concentrations must demonstrate attainment. The year 2020 was chosen because of its relevance to the ability of many areas to maintain the ozone standard. The year 2030 was chosen to provide the reader with a full sense of the reductions in ambient ozone concentrations likely to be achieved once the existing fleet of heavy-duty vehicles is replaced with vehicles meeting the standards finalized today.

The predictive ozone modeling is based on emissions inventories which have been updated and improved subsequent to the Agency's recent rulemaking on light duty vehicles and gasoline sulfur, also known as Tier 2. Areas presented in Table II.A-2 have 1997-1999 air quality data indicating violations of the 1-hour ozone NAAQS, or are within 10 percent of the standard, and are predicted to have exceedances in 2007, 2020 or 2030 without the reductions from this rule. Table II.A-2 lists those metropolitan areas with predicted exceedances of the 1-hour ozone standard in 2007, 2020, or 2030 without emission reductions from this rule (i.e., base cases). These areas are listed in columns with a "b" after the year (e.g., 2020b). Table II.A-2 also lists those metropolitan areas with predicted exceedances of the 1-hour ozone standard in 2020 and 2030, with emission reductions from this rule (i.e., control case). These areas are listed in columns with a "c" after the year (e.g., 2020c). An area was considered likely to have future exceedances if exceedances were predicted by the model, and the area is currently violating the 1-hour ozone standard, or is within ten percent of violating the 1-hour ozone standard.

Photochemical ozone modeling conducted for this rulemaking was based in part on updated national emissions inventories for all sources. National emission trends for NO_x predict a significant decline from 1996 to 2007, a leveling off of the downward trend between 2007 to 2020, and an increase in NO_x inventories from 2020 to 2030. By 2030, national NO_x levels are

estimated to reach levels that are within ten percent of 2007 levels. Predictions of national VOC emissions indicate a reduction from 1996 to 2007, followed by an increase between 2007 and 2030 resulting in 2030 levels that are estimated to be 10 percent greater than VOC emissions levels in 2007. In metropolitan ozone nonattainment areas, such as Charleston, Chicago and Houston, NO_x or VOC emissions in 2030 are predicted to reach or exceed 2007 levels. These estimated national and metropolitan area emissions inventories of ozone precursors are consistent with the conclusions reached by analysis of ozone modeling conducted for this rule that additional reductions are needed in order to enable areas to reach and maintain attainment of the ozone standard between 2007 and 2030.

In addition, the substantial reductions from today's rule will greatly lower ozone concentrations which will help federal and State efforts to bring about attainment with the current 1-hour ozone standard. As described in the Air Quality Modeling Technical Support Document for this rule, EPA performed regional scale ozone modeling for the Eastern U.S. to assess the impacts of the controls in this rule on predicted 1-hour ozone exceedances. The results of this modeling were examined for those 37 areas in the East for which EPA's modeling predicted exceedances in 2007, 2020 and/or 2030 and current 1-hour design values are above the standard or within 10 percent of the standard. The results for these areas combined indicate that there will be substantial reductions in the number of exceedances and the magnitude of high ozone concentrations in both 2020 and 2030 due to this rule. The modeling also indicates that without the rule exceedances would otherwise increase by 37 percent between 2020 and 2030 as growth in emissions offsets the reductions from Tier 2 and other current control programs.

For all areas combined, the rule is forecast to provide a 33 percent reduction in exceedances in 2020 and a 38 percent reduction in 2030. The total amount of ozone above the standard is expected to decline by nearly 37 percent in 2020 and 44 percent in 2030. Also, daily maximum ozone exceedances are lowered by 5 ppb on average in 2020 and nearly 7 ppb in 2030. The modeling forecasts an overall net reduction of 39 percent in exceedances from 2007, which is close to the start of this program, to 2030 when controls fully in place. In addition, the results for each individual area indicates that all areas are expected to have less exceedances in 2030 with the HDV controls than without this rule.

Table II.A-2. Eastern Metropolitan Areas with Modeled Exceedances of the 1-Hour Ozone Standard in 2007, 2020, or 2030 With and Without Emission Reductions from this Rule

MSA or CMSA / State	2007b	2020b	2020c	2030b	2030c	pop (1999)
Atlanta, GA MSA	x	x	x	x	x	3.9
Barnstable-Yarmouth, MA MSA *	x			x		0.2
Baton Rouge, LA MSA	x	x	x	x	x	0.6
Beaumont-Port Arthur, TX MSA	x	x	x	x	x	0.4
Benton Harbor, MI MSA *	x	x	x	x	x	0.2
Biloxi-Gulfport-Pascagoula, MS MSA *	x	x	x	x	x	0.3
Birmingham, AL MSA	x	x	x	x	x	0.9
Boston-Worcester-Lawrence, MA CMSA	x	x	x	x	x	5.7
Charleston, WV MSA *	x	x	x	x		0.3
Charlotte-Gastonia-Rock Hill, NC MSA	x	x	x	x	x	1.4
Chicago-Gary-Kenosha, IL CMSA	x	x	x	x	x	8.9
Cincinnati-Hamilton, OH-KY-IN CMSA *	x	x	x	x	x	1.9
Cleveland-Akron, OH CMSA *	x	x	x	x	x	2.9
Detroit-Ann Arbor-Flint, MI CMSA	x	x	x	x	x	5.4
Grand Rapids-Muskegon-Holland, MI MSA*	x	x	x	x	x	1.1
Hartford, CT MSA	x	x	x	x	x	1.1
Houma, LA MSA *	x	x	x	x	x	0.2
Houston-Galveston-Brazoria, TX CMSA	x	x	x	x	x	4.5
Huntington-Ashland, WV-KY-OH MSA	x	x	x	x	x	0.3
Lake Charles, LA MSA *	x	x		x	x	0.2
Louisville, KY-IN MSA	x	x	x	x	x	1
Macon, GA MSA	x	x		x		0.3
Memphis, TN-AR-MS MSA	x	x	x	x	x	1.1
Milwaukee-Racine, WI CMSA	x	x	x	x	x	1.7
Nashville, TN MSA	x	x	x	x	x	1.2
New London-Norwich, CT-RI MSA	x	x	x	x	x	0.3
New Orleans, LA MSA *	x	x	x	x	x	1.3
New York-Northern NJ-Long Island, NY-NJ-CT-PA CMSA	x	x	x	x	x	20.2
Norfolk-Virginia Beach-Newport News, VA-NC MSA *	x	x		x	x	1.6
Orlando, FL MSA *	x	x	x	x	x	1.5
Pensacola, FL MSA	x					0.4
Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD CMSA	x	x	x	x	x	6
Providence-Fall River-Warwick,RI-MAMSA*	x	x	x	x	x	1.1
Richmond-Petersburg, VA MSA	x	x	x	x	x	1
St. Louis, MO-IL MSA	x	x	x	x	x	2.6
Tampa-St. Petersburg, FL MSA *	x	x	x	x		2.3
Washington-Baltimore	x	x	x	x	x	7.4
Total number of areas	37	35	32	36	32	
Population	91.2	90.6	88.5	90.8	87.8	91.4

* These areas have registered 1997-1999 ozone concentrations within 10 percent of standard.

The inventories that underlie the photochemical ozone modeling conducted for this rulemaking included reductions from all current or committed federal, State and local controls and, for the control case, the Heavy-Duty Vehicle and Diesel Fuel Sulfur Program itself. It did not attempt to examine the prospects of areas attaining or maintaining the ozone standard with possible future controls (i.e., controls beyond current or committed federal, State and local controls). Therefore, Table II.A-2 should be interpreted as indicating what areas are at risk of ozone violations in 2007, 2020 or 2030 without federal or State measures that may be adopted and implemented after this rulemaking is finalized. We expect many of the areas listed in Table II.A-2 to adopt additional emission reduction programs, but the Agency is unable to quantify or rely upon future reductions from additional State programs since they have not yet been adopted.

The Agency recently redesignated Cincinnati-Hamilton, OH-KY-IN to attainment on June 19, 2000. This determination is based on four years of clean air quality monitoring data from 1996 to 1999 (1999 data was not considered in the Tier 2 air quality analysis or the proposal for this rulemaking), and a downward emissions trend. In today's action, Cincinnati-Hamilton is considered to have some risk of registering exceedances of the 1-hour ozone standard during the time period when the HD vehicle standards would take effect. This determination is based on air quality monitoring analysis and 1999 data with concentrations within 10 percent of the standard. Given these circumstances, the risk of future exceedances occurring in the Cincinnati-Hamilton area is most prevalent in the time period beyond the end date of Cincinnati's proposed 10-year maintenance plan (i.e., after 2010). As discussed in more detail in the relevant portions of the response to comment document for the Cincinnati-Hamilton attainment determination, any emissions and ozone modeling system used to predict future ozone involves approximations and uncertainties, and are best treated as indicators of risk rather than absolute forecasts. Thus a determination made in this rule that there is some risk of future exceedances during the relevant time period is not inconsistent with EPA approval of Cincinnati's redesignation to attainment, and its approval of Cincinnati's 10-year maintenance plan.⁷

d. Ozone Modeling and Analysis in 1-Hour State Implementation Plan Submittals and Other Local Ozone Modeling

i. Overview

We have compared and supplemented our own ozone modeling with other modeling studies, submitted to us as state implementation plan (SIP) revisions, or brought to our attention through our consultations with states on SIP revisions that are in development. The ozone modeling in the SIP revisions has the advantage of using emission inventories that are more specific to the area being modeled, and of using meteorological conditions selected specifically for each area. Also, the SIP revisions included other evidence and analysis, such as analysis of air quality and emissions trends, observation based models that make use of data on concentrations of ozone precursors, alternative rollback analyses, and information on the

responsiveness of the air quality model. For some areas, we decided that the predictions of future ozone concentrations from our modeling were less reliable than conclusions that could be drawn from this additional evidence and analysis. For example, in some areas our episodes did not capture the meteorological conditions that have caused high ozone, while local modeling did so. Thus, these local analyses are considered to be more extensive than our own modeling for estimating whether there would be NAAQS nonattainment without further emission reductions, when interpreted by a weight of evidence method which meets our guidance for such modeling.

We have reviewed and recently proposed action on SIP submissions from 13 states and the District of Columbia covering 10 serious and severe 1-hour ozone nonattainment areas. We received these submissions as part of the three-phase SIP process described by EPA guidance memos or as part of a request for an attainment date extension. These submissions also provided ozone modeling results for two attainment areas in a downwind state. These submissions contain local ozone modeling which we considered along with the results of the EPA ozone modeling conducted for this rule. We have also considered ozone modeling submitted as part of an attainment date extension requests for Beaumont-Port Arthur, TX, and Dallas/Fort Worth, TX. Finally, we have considered information in the most recent SIP submittal from California for the South Coast Air Basin. Table II.A-3 lists the areas involved, whether the modeling indicates attainment without further reductions and the Federal Register citation for our proposed action if applicable. This section discusses the background for the submissions and our findings base on them.

It is important to note that the information contained in this section on current and future ozone nonattainment is current as of December 1, and there may have been recent developments in some areas that are not incorporated here.

The local modeling analyses generally cover a modeling domain encompassing one or a few closely spaced nonattainment areas and a limited upwind area. Because of this limited domain, states have been able to use grid cells of 4 or 5 kilometers on a side, in keeping with EPA guidance for such modeling. The future attainment date examined differs from State to State depending on its current (or proposed extended) attainment deadline. In the State modeling, ozone episode days were selected by the respective states based on days with high ozone in the local domain being modeled. In all cases, we are proposing to find that the selection of episode days met our guidance. The local modeling also may make use of location-specific emission data and control programs than is practicable to include in regional-scale modeling by EPA as described above.

The SIP submissions for the 13 states and the District of Columbia covering 10 nonattainment areas contain many legally required elements in addition to the attainment demonstrations. After considering the attainment demonstrations and these other elements, we have proposed appropriate action on each of these submissions. In many cases, we have

proposed alternative actions on our part, based on whether the state submits additional SIP elements which we have described as necessary. We also explained what each state must provide us in order to allow us to take final approval or conditional approval action.

More specific descriptions of the ozone modeling contained in the SIPs, for areas where we have recently proposed action on a submittal, and more explanation of our evaluation of it can be obtained in the individual Federal Register notices and in the technical support document prepared for each action.

Table II.A-3. Nonattainment Areas For Which EPA Has Proposed Action On SIP Submissions Containing 1-hour Ozone Attainment Demonstrations or Otherwise Has Considered Results of Local Ozone Modeling

Nonattainment Area (Major Metro Area)	Affected States	Attainment Date	Indicates Attainment Without “Further Reductions”
Western Massachusetts* (Springfield)	MA	2003 (Requested Extension)	Yes
Greater Connecticut (Hartford and other MSAs)*	CT	2007 (Requested Extension)	Yes, but CT’s extension request is based on Greater CT’s inability to attain because it is affected by transport from the NYC Metropolitan Area.
New York City*	NY, CT, NJ	2007	No
Philadelphia*	PA, NJ, DE, MD	2005	No
Baltimore*	MD	2005	No
Washington, D.C.*	MD, VA, D.C.	2005 (Requested Extension)	Yes
Atlanta*	GA	2003 (Requested Extension)	No
Houston*	TX	2007	No
Chicago*	IL, IN	2007	Revised SIP attainment modeling accounts for reductions from this rule.
Milwaukee*	WI	2007	Revised SIP attainment modeling accounts for reductions from this rule.
Benton Harbor	MI	N/A	Revised SIP attainment modeling accounts for reductions from this rule.
Grand Rapids	MI	N/A	Revised SIP attainment modeling accounts for reductions from this rule.
Dallas	TX	2007 (Requested Extension)	No
Beaumont-Port Arthur	TX	2007 (Requested Extension)	EPA weight of evidence proposed approval based in part of reductions from this rule.
South Coast Air Basin	CA	2010	No

* Proposed for Action in December 16, 1999 Federal Register (64 FR 70318).

ii. Local Ozone Modeling in SIP Submissions

The EPA provides that states may rely on a modeled attainment demonstration supplemented with additional evidence to demonstrate attainment. In order to have a complete modeling demonstration submission, states have submitted the required modeling analysis and identified any additional evidence that EPA should consider in evaluating whether the area will attain the standard.

For purposes of demonstrating attainment, the CAA requires serious and severe areas to use photochemical grid modeling or an analytical method EPA determines to be as effective. The EPA has issued guidance on the air quality modeling that is used to demonstrate attainment with the 1-hour ozone NAAQS.⁸ The photochemical grid model is set up using meteorological conditions conducive to the formation of ozone. Emissions for a base year are used to evaluate the model's ability to reproduce actual monitored air quality values and to predict air quality changes in the attainment year due to the emission changes which include growth up to and controls implemented by the attainment year. A modeling domain is chosen that encompasses the nonattainment area. Attainment is demonstrated when all predicted concentrations inside the modeling domain are at or below the NAAQS or at an acceptable upper limit above the NAAQS permitted under certain conditions by EPA's guidance. When the predicted concentrations are above the NAAQS, an optional weight of evidence determination, which incorporates but is not limited to other analyses such as air quality and emissions trends, may be used to address uncertainty inherent in the application of photochemical grid models.

The EPA guidance identifies the features of a modeling analysis that are essential to obtain credible results. First, the State must develop and implement a modeling protocol. The modeling protocol describes the methods and procedures to be used in conducting the modeling analyses and provides for policy oversight and technical review by individuals responsible for developing or assessing the attainment demonstration (State and local agencies, EPA Regional offices, the regulated community, and public interest groups). Second, for purposes of developing the information to put into the model, the State must select air pollution days, i.e., days in the past with bad air quality, that are representative of the ozone pollution problem for the nonattainment area. Third, the State needs to identify the appropriate dimensions of the area to be modeled, i.e., the domain size. The domain should be larger than the designated nonattainment area to reduce uncertainty in the boundary conditions and should include large upwind sources just outside the nonattainment area. In general, the domain is considered the local area where control measures are most beneficial to bring the area into attainment. Fourth, the State needs to determine the grid resolution. The horizontal and vertical resolutions in the model affect the dispersion and transport of emission plumes. Artificially large grid cells (too few vertical layers and horizontal grids) may dilute concentrations and may not properly consider impacts of complex terrain, complex meteorology, and land/water interfaces. Fifth, the State needs to generate meteorological conditions that describe atmospheric conditions and emissions

inputs. Finally, the State needs to verify the model is properly simulating the chemistry and atmospheric conditions through diagnostic analyses and model performance tests. Once these steps are satisfactorily completed, the model is ready to be used to generate air quality estimates to support an attainment demonstration.

The modeled attainment test compares model predicted 1-hour daily maximum concentrations in all grid cells for the attainment year to the level of the NAAQS. A predicted concentration above 0.124 ppm ozone indicates that the area is expected to exceed the standard in the attainment year and a prediction at or below 0.124 ppm indicates that the area is expected to attain the standard. This type of test is often referred to as an exceedance test. The EPA's guidance recommends that states use either of two modeled attainment or exceedance tests for the 1-hour ozone NAAQS: a deterministic test or a statistical test.

The deterministic test requires the State to compare predicted 1-hour daily maximum ozone concentrations for each modeled day^e to the attainment level of 0.124 ppm. If none of the predictions exceed 0.124 ppm, the test is passed.

The statistical test takes into account the fact that the form of the 1-hour ozone standard allows exceedances. If, over a three-year period, the area has an average of one or fewer exceedances per year, the area is not violating the standard. Thus, if the State models a very extreme day, the statistical test provides that a prediction above 0.124 ppm up to a certain upper limit may be consistent with attainment of the standard. (The form of the 1-hour standard allows for up to three readings above the standard over a three-year period before an area is considered to be in violation.)

The acceptable upper limit above 0.124 ppm is determined by examining the size of exceedances at monitoring sites which *meet or attain* the 1-hour NAAQS. For example, a monitoring site for which the four highest 1-hour average concentrations over a three-year period are 0.136 ppm, 0.130 ppm, 0.128 ppm and 0.122 ppm is attaining the standard. To identify an acceptable upper limit, the statistical likelihood of observing ozone air quality exceedances of the standard of various concentrations is equated to severity of the modeled day. The upper limit generally represents the maximum ozone concentration level observed at a location on a single day and it would be the only level above the standard that would be expected to occur no more than an average of once a year over a three-year period. Therefore, if the maximum ozone concentration predicted by the model is below the acceptable upper limit, in this case 0.136 ppm, then EPA might conclude that the modeled attainment test is passed. Generally, exceedances well above 0.124 ppm are very unusual at monitoring sites meeting the NAAQS. Thus, these upper limits are rarely significantly higher than the attainment level of 0.124 ppm.

^e The initial, "ramp-up" days for each episode are excluded from this determination.

When the modeling does not conclusively demonstrate that the area will attain, additional analyses may be presented to help determine whether the area will attain the standard. As with other predictive tools, there are inherent uncertainties associated with modeling and its results. For example, there are uncertainties in some of the modeling inputs, such as the meteorological and emissions data bases for individual days and in the methodology used to assess the severity of an exceedance at individual sites. The EPA's guidance recognizes these limitations, and provides a means for considering other evidence to help assess whether attainment of the NAAQS is likely. The process by which this is done is called a weight of evidence (WOE) determination.

Under a WOE determination, the State can rely on and EPA will consider factors such as other modeled attainment tests, e.g., a rollback analysis; other modeled outputs, e.g., changes in the predicted frequency and pervasiveness of exceedances and predicted changes in the design value; actual observed air quality trends; estimated emissions trends; analyses of air quality monitored data; the responsiveness of the model predictions to further controls; and, whether there are additional control measures that are or will be approved into the SIP but were not included in the modeling analysis. This list is not an exclusive list of factors that may be considered and these factors could vary from case to case. The EPA's guidance contains no limit on how close a modeled attainment test must be to passing to conclude that other evidence besides an attainment test is sufficiently compelling to suggest attainment. However, the further a modeled attainment test is from being passed, the more compelling the WOE needs to be.

Special explanation is necessary on the issue of how the NO_x SIP Call/Regional Ozone Transport Rule has been handled by states in their local ozone modeling. In most of the local ozone modeling in these SIP revisions, upwind NO_x reductions have been assumed to occur through implementation of the NO_x SIP Call/Regional Ozone Transport Rule in some or all of the states subject to that rule, even though all states' rules to implement those reductions have not yet been adopted. Where upwind and local implementation of the NO_x SIP Call is assumed, our conclusion that the modeling shows that an area cannot attain the NAAQS means that it cannot attain even with the prior implementation of the NO_x SIP Call.^f For the purpose of this rule, EPA has incorporated the emission reductions from the NO_x SIP Call into its evaluation of whether further reductions are needed. Absent such reductions, the need for additional reductions is even greater.

^f Our recent proposals on the SIPs explain how we propose to approach the approval of 1-hour attainment SIPs themselves with respect to the NO_x SIP Call. To summarize, we have proposed to approve a SIP which assumes implementation of the NO_x SIP Call provided that the State is committed to implementing the NO_x reductions within the in-State portion of the modeling domain of the subject nonattainment area. Reductions outside the domain and in other states may be assumed even if a commitment is currently lacking for those areas.

iii. Conclusions from the Local Modeling in SIP Submittals

As discussed previously, we have recently been able to review ozone modeling and other evidence on the likelihood of attainment for ten major metropolitan nonattainment areas. The local modeling only addresses the current and requested attainment date in each area. For the areas involved, these dates fall between 2003 and 2007. The State and local ozone modeling therefore does not address attainment prospects beyond 2007. In December, 1999, the Agency proposed to approve attainment demonstrations for these 10 areas, in some cases with, and in others without, a requirement that states adopt additional measures. More recently, we proposed to approve an attainment demonstration for St. Louis.

All of the states have made use of the weight of evidence concept in their attainment demonstrations. EPA has proposed to find that some of the demonstrations are adequate, while for others additional reductions are needed to attain. We are in some cases proposing to approve demonstrations that depend on emission reductions from measures that the State has not yet adopted and has not yet made a legally enforceable commitment to adopt and implement. Before we take final and unconditional action on an attainment demonstration in such a case, the state will have to adopt all the necessary rules or make enforceable commitments to adopt them.

These State-specific conclusions are not final and we are not making them final via this rule on heavy-duty vehicles. In our final actions on these SIP revisions, we may deviate from our proposal for one or more areas, based on the full record of the rulemaking for each, including any comments received after today. However, we have used the ozone attainment assessments as described below in analyzing the need for additional emission reductions in these areas.

For the New York Metro area, Philadelphia, Baltimore, and Houston nonattainment areas, the EPA has proposed to determine that additional emission reductions beyond those provided by the SIP submission are necessary for attainment. A portion of that reduction will be achieved by federal actions, such as the Tier 2/Sulfur program. In the case of Washington DC, the Tier 2/Sulfur program will provide additional emission reductions needed to keep local emissions in 2005 at or below the levels needed to attain. However, as discussed subsequently, there is still a risk of future nonattainment in the Washington, DC area in 2007 and later due to inherent uncertainties in air quality forecasting and future exceedances predicted by Tier 2 air quality modeling.

As a result of EPA's review of the states' SIP submittals, EPA believes that the ozone modeling submitted by the applicable states for the Chicago, IL, Greater CT (Hartford and New London metropolitan areas), Southeast Desert, and Milwaukee, WI areas demonstrated attainment through the control measures contained in the submitted attainment strategy. Illinois, Indiana, and Wisconsin must submit further SIP revisions, including updated modeling for the Chicago and Milwaukee nonattainment areas by December 2000. For these areas, the updated

regional ozone modeling conducted by the Lake Michigan Air Directors Consortium on behalf of the states relies in part on reductions from this rulemaking.^g Thus, the 2007 attainment demonstrations for these areas will be based in part on reductions from this rule.

Greater Connecticut and the Southeast Desert are subject to transport from upwind areas that need additional reductions in order to reach attainment in 2007 (New York City), or 2010 (South Coast Air Basin).^h If attainment is not achieved by New York and South Coast, it is unlikely that Greater Connecticut and the Southeast Desert will achieve attainment. Since New York and the South Coast need further reductions that this rule will in part satisfy, reductions from this rule will also assist downwind nonattainment areas such as Greater Connecticut and the Southeast Desert to reach attainment in 2007 and maintain the ozone NAAQS in future years.

Atlanta's statutory attainment date as a serious 1-hour ozone nonattainment area was November 1999, which it has not met. Georgia has requested an attainment date extension for Atlanta to November 15, 2003 and has proposed an emission control program to achieve attainment by that date. The EPA has proposed to assign Atlanta an attainment date of November 2003 based on a successful demonstration by the State that the control strategy described in the SIP will achieve attainment by this date. All of the measures in that strategy – as well as the measures identified as “additional measures” that were not modeled but needed for attainment in the weight of evidence analyses – have been adopted. It is clear from the amount of emission reductions from these measures that the nonattainment status of Atlanta would extend into the 2004 and later period if only “previous” emission reductions (i.e., reductions in the modeled strategy) were considered. The modeling for Atlanta assumed implementation of the NO_x SIP Call outside the local modeling domain. The NO_x reductions relied on in the Atlanta SIP local modeling domain are slightly greater than the NO_x reductions that are expected to be achieved under the NO_x SIP call.

The specific reasons for reaching these conclusions are explained in the individual Federal Register notices.

^g Lake Michigan Air Directors Consortium. Midwest Subregional Modeling: 1-Hour Attainment Demonstration - Tier II/Low Sulfur Controls. November 8, 1999.

^h EPA approved the South Coast's “additional measures” relying on new technologies under Clean Air Act section 182(e) in 1995. 60 FR 43379 (August 21, 1995). Emissions reduction shortfall was quantified at 60 tons per day (tpd) for NO_x, and 79 tps of VOC. These measures are discussed in the 1994 California SIP (Volume I, p. I-33, I-35 and Volume II, p. I-29, I-31). In addition, EPA found shortfalls remaining in the mobile source emissions reductions needed for attainment of the 1-hour ozone standard in the South Coast (64 FR 39923-27, July 23, 1999).

iv. Other Local Ozone Modeling and Ozone Nonattainment Prospects

The photochemical ozone modeling conducted for this rule did not predict exceedances for a number of areas for which other available information, such as local ozone modeling, inventory and air quality trends, demonstrates a risk of future exceedances between 2007 and 2030. Table II.A-4 lists these eight areas. These eight areas will be discussed in subsequent sections along with the 37 areas with predicted ozone exceedances in 2007, 2020, or 2030 (Table II.A-2).

We have received ozone modeling for the Beaumont-Port Arthur nonattainment area.⁹ Beaumont-Port Arthur is a moderate ozone nonattainment area which continues to have concentrations above levels of the 1-hour ozone NAAQS. Presently, the State of Texas is seeking our approval for a demonstration that Beaumont-Port Arthur is impacted by ozone transport from the Houston area, in order to support a request that we extend its attainment deadline to 2007 which would be the same as the deadline for Houston. We proposed action on this request on April 16, 1999 (64 FR 18864) and extended the comment period on June 3, 1999 (64 FR 29822). Our Proposed Action indicated that we would approve the attainment date extension request if Texas met several necessary conditions, one of which was submission of an approvable demonstration of attainment showing attainment by that date. Texas submitted revisions to the Beaumont/Port Arthur SIP on November 15, 1999 and April 28, 2000. The modeling analysis in these SIP revisions indicates that after implementation of the State's adopted control strategy nonattainment continues. The State supplied additional evidence to indicate that the area is likely to attain the Standard based on EPA's weight of evidence guidance. We have considered the additional reductions from this rule as part of our proposed action on the State's attainment demonstration.

Texas also submitted a modeling analysis and attainment date extension request for the Dallas-Fort Worth metropolitan area on April 28, 2000.¹⁰ The State has requested to extend the attainment date to 2007. The SIP revision includes the State's adopted control strategy and a modeling analysis and weight of evidence demonstration. Our preliminary finding is that the combined modeling and weight of evidence analysis has little if any margin of safety for demonstrating attainment. The Agency's expects that any future proposed determination of the SIP attainment demonstration submitted by Dallas, TX, using meteorology conditions and other inputs selected to be locally applicable, would rely in part on reductions from this rule.

Table II.A-4. Areas With Some Risk of Ozone Violations between 2007 and 2030 Based on Information Other Than Predictive Ozone Modeling

Metropolitan Areas	Basis for Need of Additional Reductions	1999 Population (in millions)
Dallas, TX	Agency expects to rely on reductions from this rule in its proposed weight of evidence determination for the Dallas SIP.	4.9
South Coast Air Basin, CA (Los Angeles-Riverside-San Bernardino)	Emission reduction shortfalls (NO _x and VOC) identified in current SIP.	16.0
San Diego, CA	Transport from South Coast Air Basin.	2.8
Southeast Desert, CA	Transport from South Coast Air Basin, significant ozone levels and number of exceedance days (1997-1999).	0.5
Sacramento, CA	Significant ozone levels and number of exceedance days (1997-1999).	1.7
Ventura County, CA	Transport from South Coast Air Basin	0.7
San Joaquin Valley, CA	Area needs to revise SIP for bump-up to severe (2005); significant ozone levels and number of exceedance days (1997-1999)	3.2
San Francisco, CA	Area needs to revise its SIP, significant ozone levels and number of exceedance days (1997-1999).	6.9
8 areas		36.8

We have not received any recent ozone modeling from California, because California submitted and we approved the SIPs for nonattainment areas in California some time ago. It is appropriate for us to consider the need for further emission reductions in order for areas in California to attain and maintain. California contains many of the most ozone-impacted areas in the nation. Nine areas in California currently designated as nonattainment (and two counties currently designated as being in attainment) with a population of approximately 32 million have

1997-1999 design values above the 1-hour ozone NAAQS. Seven of the nonattainment areas have approved SIPs, including demonstrations of attainment for their required date. Emissions reductions expected from federal programs, such as the Tier 2/Sulfur rule, represent only a small fraction of the emission reductions needed in the South Coast to attain the NAAQS.

Ozone levels in the South Coast Air Basin have declined over the last two decades, but this area continues to register some of the highest ozone concentrations and the greatest number of exceedance days in the nation. In the three year period from 1997 to 1999, the South Coast recorded a peak ozone level of 0.211 ppm and averaged 39 days above the 1-hour ozone standard. The South Coast has an approved SIP, but it contains shortfalls that must be filled if the area is to reach attainment in 2010. The South Coast generates ozone and ozone precursors that affect the air quality and attainment prospects of downwind areas such as Ventura County,ⁱ San Diego, and the Southeast Desert.

The transport of ozone and its precursors from the South Coast to downwind areas such as the San Diego, Ventura County and the Southeast Desert has been established by the California Air Resources Board.^j In addition to receiving transport from the South Coast, the Southeast Desert registered a significant peak ozone concentrations of 0.170 ppm and exceeded the 1-hour ozone standard 24 days on average between 1997-1999. While these areas may have earlier attainment dates, their ability to attain the ozone NAAQS depends in part on attainment by the South Coast. Reductions from this action will provide NO_x and VOC reductions needed to help fill shortfalls identified in the South Coast's approved SIP. By extension, since attainment in the South Coast would assist efforts to reach attainment in Ventura and the Southeast Desert by their respective deadlines (2005 and 2007), these two areas, along with San Diego, are also dependent on South Coast reductions associated with today's action to maintain attainment in the future.

We expect that California will be submitting one or more revisions since it appears that one unclassified nonattainment area with a 2000 attainment deadline and one serious classification nonattainment area in California with an attainment deadline of 1999 have not met that date. These areas are San Francisco and the San Joaquin Valley. San Francisco had a violation in its attainment year (2000), which may require the area to submit a revised attainment

ⁱ *Assessment and Mitigation of the Impacts of Transported Pollutants on Ozone Concentrations within California*, California Air Resources Board, June, 1990. This photochemical grid model analysis found that on some days emissions from the South Coast Air Basin contribute in a significant way to ozone concentrations in Ventura County.

^j Regulations on "Rulemaking on the Assessment of the Impacts of Transported Pollutants on Ozone Concentrations in California" were approved by the California Office of Administrative Law on August 27, 1997. Note that for purposes of the CARB's transport assessment, the Southeast Desert is divided into two air basins: the Mojave Desert Air Basin and the Salton Sea Air Basin (Title 17, CA Code of Regulations, 60104, 60109, 60114).

plan. From 1997 to 1999, the area registered a peak ozone value of 0.139 ppm and averaged about 3 exceedance days per year. San Francisco does not currently have an attainment classification.

San Joaquin has had too many exceedances to be eligible for an extension and EPA has proposed to bump-up the area to severe classification with a 2005 attainment date. From 1997 to 1999, the area recorded a peak ozone level of 0.161 ppm and exceeded the ozone standard 14 days on average. In fact, since 1991, the area has consistently registered peak ozone levels of around 0.160 ppm. The magnitude and persistence of peak ozone levels in San Joaquin Valley is an important factor to consider when attempting to assess future attainment prospects.

Sacramento has an approved SIP. However, between 1997-1999, the area registered a peak ozone concentration of 0.148 ppm and five exceedances days per year on average. These ozone levels and number of exceedance days suggest that this area has some risk of not attaining the standard by its attainment date.

San Diego is subject to transport from the South Coast Air Basin, and has registered significant ozone levels from 1997-1999. This area was granted a 1-year attainment date extension under the provisions of CAA section 181(a)(5), and appears to be eligible for a second 1-year attainment date extension based on clean air in 2000.

v. *Areas At Risk of Exceeding the 1-Hour Ozone Standard in the Future*

This section collects the information previously presented on the attainment prospects of areas across the nation based on both photochemical ozone modeling and other local factors such as magnitude and persistence of ozone exceedances, emissions inventory trends, local modeling, SIP status, and transport from areas with later attainment dates.^k The Agency's conclusions about the risk of future nonattainment is provided in Table II.A-6, which is separated into two broad groups: (1) those areas with attainment dates in 2007 or 2010 that will benefit from reductions from this rule to attain and maintain the standard; and (2) those areas with attainment dates prior to 2007 that will benefit from reductions from this rule to maintain the standard after their attainment dates. Because ozone concentrations causing violations of the 1-hour ozone standard are well established to endanger public health and welfare, this indicates that it is appropriate for the Agency to set new standards for heavy-duty vehicles.

^k In the proposal, we relied on photochemical ozone modeling performed for recently promulgated standards on light duty vehicles, or Tier 2. The results presented in this final rulemaking for heavy-duty vehicles and diesel fuel are largely consistent with the findings presented in the proposal, with small differences due to updated emissions inventories. As stated in the proposal, the ozone modeling methodologies used in the proposal and presented here in the final rule are identical.

vi. Areas with 2007 or 2010 Attainment Deadlines

The Clean Air Act requires states to submit a SIP to provide for attainment of the 1-hour ozone standard which includes a demonstration of attainment (including air quality modeling) for their nonattainment areas, as well as emission control measures needed to attain by the attainment date. Once the attainment date arrives, areas that have not attained the standard based on monitoring data are subject to applicable provisions of the Clean Air Act, including the possibility of being required to adopt additional emission control measures. Areas that have attained the standard have the option of applying for redesignation to attainment status, which can permit adjustments in the emission control program.

Table II.A-5 identifies ten ozone nonattainment areas with attainment dates of 2007 or 2010. These ten areas are also listed on the top section of Table II.A-6, which is located at the end of this subsection. Each of these areas will need additional reductions to attain the ozone standard, and will also be able to rely on additional reductions from today's action in order to maintain the standard. There are specific emission reduction shortfalls in attainment SIPs submitted for New York, Houston and the South Coast Air Basin based on the local ozone modeling and other evidence. The Agency has not identified a shortfall in the attainment demonstrations submitted by Greater Connecticut (Hartford and New London, CT), but we have proposed to approve an extension date to 2007 based on Greater Connecticut being unable to attain because it is affected by transport from the New York metropolitan area. Transport of ozone and its precursors from the South Coast to the Southeast Desert, San Diego, and Ventura County hinders the ability of these areas to attain the standard. There is some risk that New York will fail to attain the standard by 2007, and thus a transferred risk that Connecticut will also fail. A similar situation exists in Southern California, where attainment of the South Coast is a precondition of the ability of three downwind areas -- Southeast Desert, San Joaquin Valley, and Ventura County to reach attainment by their respective attainment dates. Additional reductions from this rule will assist New York and Greater Connecticut, and the South Coast and its downwind nonattainment areas, in reaching the standard by each areas' respective attainment date, and maintaining the standard from attainment to 2030.

Chicago and Milwaukee originally submitted modeling which did not indicate a need for additional local reductions. However, required, updated modeling for these two areas relies in part on reductions from this rule.¹ Moreover, the ozone modeling for this rulemaking predicted exceedances in Chicago and Milwaukee in 2007, 2020 and 2030.

¹ *Technical Support Document, Midwest Subregional Modeling: 1-Hour Attainment Demonstration for Lake Michigan Area and Emissions Inventory*, Illinois Environmental Protection Agency, Indiana Department of Environmental Management, Michigan Department of Environmental Quality, Wisconsin Department of Natural Resources, September 27, 2000, at 14 and at 8.

Dallas and Beaumont Port-Arthur, TX have requested attainment date extensions to 2007 on the grounds that 2007 is the attainment date for Houston and that local air quality is affected by transport from Houston. We have proposed to grant an extension to Beaumont-Port Arthur. We have not yet proposed any action on Dallas. The State of Texas has developed an attainment plan for Dallas, which is a precondition for granting extensions based on transport. In a recently proposed action on attainment SIP submitted for Beaumont-Port Arthur, we have proposed approval based in part on the Agency's weight of evidence determination that included in its consideration expected reductions from today's action. We expect that we will also consider reductions from today's action in our action on the Dallas/Fort Worth plan. Furthermore, EPA's ozone modeling indicated exceedances in Beaumont Port-Arthur in 2007. Although there were no exceedances predicted in the future-year scenarios for Dallas in the modeling by EPA, the episodes used by the state in their local modeling did predict future-year exceedances. We do currently believe these two areas are likely to violate the NAAQS between 2007 and 2030, without more emission reductions in the local areas, and/or from the upwind Houston area, and/or from today's action.

The Los Angeles (South Coast Air Basin) ozone attainment demonstration is fully approved, but it is based in part on reductions from new technology measures that have yet to be identified. The 2007 attainment demonstration for the Southeast Desert area is also approved. However, a transport situation exists between the Southeast Desert areas and the South Coast Air Basin, such that attainment in the Southeast Desert depends on progress in reducing ozone levels in the South Coast Air Basin.

Table II.A-5. Metropolitan Areas With Established or Requested 2007 or 2010 Attainment Deadlines

<i>Metropolitan Area</i>	<i>Attainment Dates</i>	<i>Future Attainment Prospects</i>	<i>Metropolitan Area 1999 Population (in millions)</i>
New York City, NY-NJ-CT	2007	VOC and NOx Shortfall	20.0
Houston, TX	2007	NOx Shortfall	4.5
Hartford, CT	2007 (requested extension)	Contingent on New York Attainment	1.1
New London, CT	2007 (requested extension)	Contingent on New York Attainment	0.3
Chicago, IL-IN	2007	Updated modeling relies in part on reductions from this rule.	8.9
Milwaukee, WI	2007	Updated modeling relies in part on reductions from this rule.	1.6
Dallas, TX	2007 (requested extension)	Local modeling shows nonattainment in 2007	4.9
Beaumont-Port Arthur, TX	2007 (requested extension)	Local modeling shows nonattainment in 2007	0.4
Los Angeles, CA	2010	Approved attainment demonstration, but needs additional reductions to attain	16
Southeast Desert, CA	2007	Approved attainment demonstration, but contingent on South Coast Attainment	0.5
10 Metropolitan Areas	Total Population (in millions)		58.4

Therefore, these 10 nonattainment areas with about 58 million people will need to rely in part on the reductions from today's action to attain the 1-hour ozone standard by 2007 or 2010, and maintain the standard from 2007/2010 and 2030. We expect to rely in part on these reductions in reaching our final conclusion as to whether each area for which we have reviewed an attainment demonstration is more likely than not to attain on its respective date, whether or not the State formally relies on these reductions as part of its strategy to fill the identified shortfall in its attainment demonstration, if any. This is especially true for those areas that have shortfalls in their attainment demonstrations, or that have air quality modeling that suggests additional reductions are needed. The NO_x and VOC reductions in the early years of this program may prove to be a critical part of a range of actions necessary for these areas to overcome their shortfalls and reach attainment.

The emission reductions from this rule will also help these areas reach attainment at lower overall cost, with less impact on small businesses. Following implementation of new controls for regional NO_x reductions, states will have already adopted emission reduction requirements for most large sources of VOC and NO_x for which cost-effective control technologies are known and for which they have authority to control. Those that must adopt measures to complete their attainment demonstrations therefore will have to consider their remaining alternatives. Many of the alternatives that states may consider could be very costly, and the emissions impact from each additional emissions source subjected to new emissions controls could be considerably smaller than the emissions impact of the standards being proposed today. Therefore, the emission reductions from the standards we are finalizing today will ease the need for states to find first-time reductions from the mostly smaller sources that have not yet been controlled, including area sources that are closely connected with individual and small business activities. The emission reductions from the standards being finalized today will also reduce the need for states to seek even deeper reductions from large and small sources already subject to emission controls.

The Southeast Desert has an approved attainment demonstration, and we have proposed to approve attainment demonstrations in some of the other nine areas without additional emission reductions from local measures. Even if all shortfalls were filled for each area, this would not mean that there is no danger that ozone levels in these areas will exceed the NAAQS, in the absence of today's action. Agency approval of an attainment demonstration generally indicates our belief that a nonattainment area is reasonably likely to attain by the applicable attainment date with the emission controls in the SIP. However, such approval does not indicate that attainment is certain. Moreover, no ozone forecasting is 100 percent certain, so attainment by these deadlines is not certain, even though we believe it is more likely than not. There are significant uncertainties inherent in predicting future air quality, such as unexpected economic growth, unexpected VMT growth, the year-to-year variability of meteorological conditions conducive to ozone formation, and modeling approximations. Ozone formation is highly dependent on local weather conditions. In fact, the variability in observed ozone due to

meteorology can be larger than the ozone reductions yielded from a significant emission reduction.^m There is at least some risk in each of these ten areas that even assuming all shortfalls are filled, attainment will not be reached by the applicable dates without further emission reductions. The Agency's mid-course review in the SIP process -- as well as the Clean Air Act's provisions for contingency measures -- is part of our strategy for dealing with some of these uncertainties, but does not ensure successful attainment.

Where we have proposed a specific amount of additional reductions needed for attainment, there is a risk that violations would occur in 2007 even if the additional measures for this amount of reduction are adopted. In addition to all of the factors mentioned above in connection with the Southeast Desert and the areas for which we did not identify a shortfall, there is uncertainty in the conclusion about the existence and size of the shortfall. The shortfalls were identified through consideration of a variety of evidence, without actual ozone modeling on the effect of the additional emissions reductions.

Given the political, human, and economic factors involved, until the affected states actually submit their emission control measures to make up the shortfalls, there is some risk that the eight areas presently without approved attainment demonstrations will not adopt fully approvable SIPs. In addition, some of these SIPs assume reductions in NO_x emissions in upwind areas in other states. Until those controls are adopted and implemented, those reductions are somewhat uncertain. Also, success in implementing all the in-state measures in the SIPs once they are developed and approved is somewhat uncertain, and this contributes to the risk that 2007 attainment will not happen. This possibility contributes to the risk that each of these areas will have violations in 2007 despite all efforts to reach attainment.

If an area with a 2007 attainment date does fail to demonstrate actual attainment of the 1-hour ozone NAAQS based on 2005-2007 ozone data, the Clean Air Act allows EPA to grant it up to two one-year extensions, provided there has not been more than one exceedance of the standard in the year prior to the attainment year. The emission reductions from the rule in 2008 and 2009 will be even larger than the reductions in 2007, and can play an important role in allowing an area that needs these extensions to attain in 2008 or 2009.

^m An analysis of ambient 1-hour design values for three, 3-year time periods between 1994 and 1998 for monitoring sites in the East indicates a 10 percent swing in the 90 percent percentile design values. Thus, if an area just attains in 2007, there is a risk that it could fall back into nonattainment in subsequent time periods due to year-to-year variations in meteorology, assuming emissions do not change or change very little. The net NO_x emissions reductions due to Tier 2 in 2007 is 4 percent considering all Eastern States collectively. The Tier 2 modeling indicates that this level of NO_x reductions results in ozone reduction on the order of generally 1-3 ppb ozone. The 1-3 ppb reductions associated with the 4 percent Tier 2 NO_x reductions are small compared to the effects of variations in ozone due to meteorology. It is important to note that the episodes modeled by the Agency, though not "worst case," may be somewhat more severe for most areas than meteorological conditions associated with recent design values. Thus, modeling with these episodes that indicates attainment for an area is likely to be conservative.

The Agency regards the continuing reductions from the 2007 heavy-duty rule as part of the federal/State effort not only to reach attainment in the 2007 to 2009 time frame, but to ensure that attainment is maintained in the future. The ability of states to maintain the ozone NAAQS once attainment is reached has proved challenging, and the recent recurrence of violations of the NAAQS in some other areas increases the Agency's concern about continuing maintenance of the standard in these ten areas (and other areas discussed later) once attainment is achieved. Agency uncertainty about the prospects of continued maintenance of the standard is also due, in part, to the fact that State attainment demonstrations generally do not model beyond their particular attainment date, and EPA does not insist that states prepare maintenance plans prior to their request for redesignation to attainment after they have attained. Local modeling and our review of the SIPs did not address whether additional reductions from fleet turnover would offset factors that might cause violations after their attainment dates.

Recurrent nonattainment is especially problematic for areas where high population growth rates lead to significant annual increases in vehicle trips and vehicle miles traveled. Another factor that plays a role in long-term maintenance is meteorology. Our guidance to states on ozone modeling for attainment demonstrations is to select high ozone days that are representative of their current ozone design values. Analysis of these conditions are then used to predict future ozone and in evaluating control strategies. When assessing the risk of air pollution that would endanger public health and welfare during the period when the heavy-duty rule will reduce emissions, we think it is appropriate to consider the possibility that year-to-year variability of meteorological conditions conducive to ozone formation may be worse than this sometime in the future. In considering the period for many years beyond 2007, it is possible that some years will have meteorological conditions conducive to ozone formation substantially worse than assumed in the ozone modeling in the attainment demonstration. Moreover, ozone modeling conducted for this rule predicted exceedances in 2020 and 2030, which adds to the Agency's uncertainty about the prospect of continued attainment for these areas.

To conclude, a total of ten metropolitan areas need additional measures to meet the shortfalls in the applicable attainment demonstrations, or are subject to ozone transport from an upwind area that has an identified shortfall. EPA finds that the states responsible may need, among other reductions, the level of reductions provided by this rule in order to fill the shortfalls. We expect to rely in part on these reductions in reaching our final conclusion as to whether each of the eight areas for which we have recently reviewed an attainment demonstration is more likely than not to attain on its respective date, whether or not the State formally relies on these reductions as part of its strategy to fill the identified shortfall in its attainment demonstration. As to all ten areas, even if all shortfalls were filled by the states, there is some risk that at least some of the areas will not attain the standards by their attainment dates of 2007, or 2010 for Los Angeles. In that event, the reductions associated with this program, which increase substantially after 2007, would help assure that any residual failures to attain are remedied. Finally, there is also some risk that the areas will be unable to maintain attainment after 2007. Considered

collectively, there is a significant risk that some areas would not be in attainment throughout the period when the rule will reduce heavy-duty vehicle emissions.

vii. Areas with Pre-2007 Attainment Dates or No Attainment Date

The next group of 20 areas have required attainment dates prior to 2007, or have no attainment date but are subject to a general obligation to have a SIP that provides for attainment and maintenance. These 20 areas are found in the middle of Table II.A-6, which compiles information about the 45 areas of concern. Table II.A-6 is located at the end of this subsection. EPA and the states are pursuing the established statutory processes for attaining, and maintaining the ozone standard, where it presently applies, and EPA has re-instated the ozone standard to the remaining areas. The Agency's finding that there is a significant risk that future air quality would exceed the ozone standard at some time in the 2007 and later period is based on three factors: (1) recent exceedances in 1997- 1999, (2) predicted exceedances in 2007 or 2030 after accounting for reductions from Tier 2 and other federal, local, state or regional controls currently in place or required, and (3) our assessment of the magnitude of recent violations, the year-to-year variability of meteorological conditions conducive to ozone formation, transport from areas with later attainment dates, and uncertainty inherent in SIP attainment planning.

In addition, only a subset have yet adopted specific control measures that have allowed the Agency to approve an attainment plan, and until the SIPs are actually submitted, reviewed and approved, there is some risk that these areas will not adopt fully approvable SIPs. Furthermore, some of these areas are not under a current requirement to obtain EPA approval for an attainment plan. The mechanisms to get to attainment in areas without a requirement to submit an attainment demonstration are less automatic, and more uncertain. Even with suitable plans, implementation success is uncertain, and therefore there is some risk that 2007 attainment, or maintenance thereafter, would not happen. Maintenance plans are not required to contain enforceable measures beyond those in the conforming SIP, and all current maintenance plans will expire prior to the time when the bulk of reductions from this rule will be achieved.

Seven metropolitan areas listed in Table II.A-6 contain a 1-hour ozone nonattainment area, or areas, for which we have approved, or proposed to approve, an attainment demonstration for an attainment date of 2003 or 2005 (including granted or requested extensions). These areas include Atlanta, Philadelphia, Washington DC, Baltimore, Sacramento, Ventura County, and the San Joaquin Valley. For Atlanta, Baltimore, and Philadelphia, we have proposed that specific further emission reductions are needed in order to attain by the applicable attainment date. We have proposed to approve Washington, D.C.'s attainment demonstration without requiring additional local emission reductions beyond what the State is required to implement or has already said it will implement. However, air quality modeling conducted for this rule predicted

exceedances for Washington DC.ⁿ Baltimore has predicted exceedances under our ozone modeling and has a recognized emissions shortfalls in its attainment demonstration. We have given final approval to the attainment demonstrations for the listed areas in California. Ventura County's air quality (like that of Southeast Desert and San Diego) is greatly affected by transport from the South Coast Air Basin, and has a significant risk of registering ozone exceedances until the South Coast achieves attainment in 2010 or thereafter. Sacramento has a shortfall identified in its approved SIP. The San Joaquin Valley has an approved SIP, but has recently registered some of the highest ozone levels in the nation.

Subject to consideration of comments on our proposed approvals or other new information, we consider it more likely than not that these seven areas with proposed or final attainment demonstrations will attain by their deadlines, provided the identified additional reductions are achieved. However, as noted above for the areas with 2007 or 2010 attainment dates, there are inherent uncertainties in ozone modeling, attainment planning, and control plan implementation. All of the uncertainties and risk factors discussed above in connection with the 2007 and 2010 areas also apply to these areas. As with most of the 2007 and 2010 areas, ozone modeling predicted ozone exceedances in 2007 for many of these areas. There is some risk in each of these areas that attainment will not be reached by its deadline. Furthermore, nonattainment might persist beyond the deadline into the period when additional reductions from the this rule can assist with attainment. Recurrent nonattainment is especially problematic for areas like Atlanta, GA and Sacramento, CA, where high population growth rates lead to significant annual increases in vehicle trips and vehicle miles traveled.

There are eight metropolitan areas still subject to the 1-hour ozone NAAQS which have attainment dates of 1999 or earlier, but have experienced concentrations above the level of the 1-hour ozone NAAQS. These are Baton Rouge, Birmingham, Cincinnati, Louisville, San Diego, San Francisco (moderate, but with a 2000 attainment date), and St. Louis.^o Ozone modeling

ⁿ It is important to note that modeling conducted for this rulemaking shows that areas are at risk of exceeding the ozone standard in 2007, 2020 and 2030, and that this modeling is not related to the modeling analysis performed for the Washington, D.C. nonattainment area, which demonstrates attainment by 2007 when combined with weight of evidence arguments.

^o Ozone monitoring data showing 1997-1999 violations in Baton Rouge, Phoenix, San Diego, Sacramento, San Francisco, Southeast Desert, Ventura County and the San Joaquin Valley may in some cases still be in need of final confirmation. San Diego had a 1999 attainment date, which it did not meet. However, it experienced only one exceedance in 1999 and so is eligible for an extension to 2000, and then to 2001 if there is only one exceedance in 2000. The occurrence of only a single exceedance in 1999 arguably was attributable to unusual meteorology, and there is a good risk that attainment will not be reached even by 2001. San Francisco was originally classified as a moderate area with a 1996 attainment deadline. In 1995, the area was redesignated to attainment, but subsequently violated the NAAQS. The area was again designated nonattainment and given a 2000 attainment deadline. Data from 1998 make it clear that this area will not attain based on 1998-2000 monitoring data. Based on air quality

predicted 2007, 2020 and/or 2030 exceedances for all of the areas outside of California. The California areas have recent exceedances. San Diego is impacted by South Coast's air quality and recent violations prevent San Francisco from attaining in 2000. In addition, San Francisco is without an approved attainment plan. For some of these areas, we have not yet received, or have not proposed approval of, a SIP revision with a plan to correct the recent violations. Many of these areas may require an attainment date extension while retaining their current classification, or reclassification to a higher classification with a later attainment date. The present absence of an attainment plan increases the risk that nonattainment will persist into the 2007 and later period.

There are another eight areas of concern because of recent concentrations above the level of the 1-hour ozone NAAQS and modeled predictions of 2007 nonattainment, for which the 1-hour ozone NAAQS was recently reapplied, and are re-classified as attainment and have maintenance plans spanning 10 year periods ending between 2005 and 2008. These 8 areas are Charlotte, Grand Rapids, Huntington, Indianapolis, Memphis, Nashville, Houma, and Richmond. Houma (LaFourche Parish), LA does not have a specific attainment date.

EPA has recently reinstated the 1-hour ozone standard. There were seven areas designated attainment with maintenance plans that had violations since revocation between 1996-1998. Four of these areas -- Charlotte-Gastonia, NC, Huntington-Ashland, WV-KY, Nashville, TN, Richmond, VA -- also have predicted exceedances. Recent exceedances in these four areas will likely trigger any contingency measures in the maintenance plans that are tied to new ozone violations. However, contingencies tied to air quality were not always a required element or enforced while the standard was revoked in these maintenance plans, and the SIPs may not yet contain adequate provisions to bring these areas into consistent attainment. Our ozone modeling predicted that, even with federal and regional controls in place at the time, these areas are likely to exceed the standard in 2007, 2020 and 2030. EPA will monitor the situation in these areas, and has options for working with the affected states towards further emission reductions if needed. At this time, the Agency has not identified the specific next steps that states might appropriately take to address this situation.

A group of four areas have had the ozone standard revoked, are without maintenance plans, have experienced recent exceedances, and are predicted by ozone modeling to be nonattainment in 2007 if more emission reductions are not implemented. The ozone standard was reinstated for two of these areas -- Boston and Providence. Benton Harbor was officially an unclassifiable/ attainment area prior to the revocation of the 1-hour standard. Massachusetts and Rhode Island have been required to develop and submit new attainment demonstrations for their areas. For all the reasons discussed above in connection with other areas facing the need to

monitoring data not considered in the Tier 2 analysis and on 10 year emissions projections, the Agency has proposed to redesignate Cincinnati into attainment.

develop and implement an attainment plan, we find that there is some risk that these areas will not consistently attain the standard in 2007 and beyond without additional controls such as those proposed in this rulemaking. For Benton Harbor, there is no automatic requirement for preparation of a new attainment demonstration, adding to the uncertainty about 2007 attainment. There is some risk that these four areas will not attain the standard by 2007 or thereafter without additional control from today's action.

As with other areas discussed above, the absence of enforceable local controls that are demonstrated to be adequate to restore attainment in these areas on a long term basis supports the Agency's finding that there is some risk in these areas that air quality may violate the ozone standard in the 2007 and later period. There will remain risks even if a new plan is developed, adopted, and implemented. All maintenance plans must be revisited eight years after redesignation, and extended another 10 years. When these areas do face the task of planning for maintenance in the period beyond their current maintenance plan, the emission reductions from this rule will help them in reducing the risk of violations in that period.

For all of these 20 areas, EPA and the states are pursuing the established statutory processes for attaining and maintaining the ozone standard. However, only a subset have yet adopted specific control measures that has allowed or, we expect, will allow the Agency to approve an attainment plan. Despite the presence of statutory and regulatory requirements for those six areas, there is thus some uncertainty in whether states will adopt and implement measures to provide the additional reductions needed to attain by 2007. Given the political, human, and economic factors involved, until the SIPs are actually submitted there is some risk that the areas presently without approved attainment demonstrations will not adopt fully approvable SIPs. In addition, some of these SIPs assume reductions in NO_x emissions in upwind areas in other states, under the Regional Ozone Transport Rule. Until those controls are adopted and implemented, those reductions are uncertain. Also, success in implementing all the in-state measures in the SIPs once they are developed and approved is uncertain, and this contributes to the risk that 2007 attainment will not happen. This possibility contributes to the risk that each of these areas will have violations in 2007 or thereafter despite all efforts to achieve attainment.

viii. Areas within 10 percent of Violating the Ozone Standard

There are 15 additional metropolitan areas for which the available ozone modeling and other evidence is less clear regarding the need for additional reductions. Our own ozone modeling predicted these 15 areas to need further reductions to avoid exceedances in 2007, 2020 and/ or 2030. The recent air quality monitoring data for these areas shows ozone levels with less than a 10 percent margin below the NAAQS. We believe there is still a risk of that future ozone levels will be above the NAAQS because of the year-to-year variability of meteorological conditions conducive to ozone formation.

ix. Conclusion

In sum, without these reductions, there is a significant risk that an appreciable number of the 45 areas, with a population of 128 million people in 1999, will violate the 1-hour ozone standard during the time period when these standards will apply to heavy-duty vehicles. The evidence summarized in this section, and presented in more detail in the air quality modeling TSD, supports the Agency's finding that emissions of NO_x and VOC from heavy-duty vehicles between 2007 and 2030 will contribute to a national ozone air pollution problem that warrants regulatory action under section 202(a)(3) of the Act.

**Table II.A-6. Areas and 1999 Populations at Risk of Exceeding the Ozone Standard
between 2007 and 2030**

MSA/ CMSA / State	1999 Population (in millions)
Areas with 2007/ 2010 Attainment Dates (Established or Requested)	
Beaumont-Port Arthur, TX	0.4
Chicago-Gary-Kenosha, IL-IN-WI	8.9
Dallas-Fort Worth, TX	4.9
Hartford, CT	1.1
Houston-Galveston-Brazoria, TX	4.5
Los Angeles-Riverside-Orange County, CA	16.0
Milwaukee-Racine, WI	1.6
New London-Norwich, CT-RI	0.3
New York-Northern New Jersey-Long Island, NY-NJ-CT-PA	20.2
Southeast Desert, CA	0.5
10 areas	58.4
Areas with Pre-2007 Attainment Dates or No Specific Attainment Date, with a Recent History of Nonattainment.	
Atlanta, GA	3.9
Baton Rouge, LA	0.6
Birmingham, AL	0.9
Boston-Worcester-Lawrence, MA-HN-ME-CT	5.7
Charlotte-Gastonia-Rock Hill, NC-SC	1.4
Detroit-Ann Arbor-Fling, MI MSA	5.5
Huntington-Ashland, WV-KY-OH	0.3
Louisville, KY-IN	1.0
Macon, GA MSA	0.3
Memphis, TN-AR-MS	1.1
Nashville, TN	1.2
Philadelphia-Wilmington- Atlantic City, PA-NJ-DE-MD	6
Richmond-Petersburg, VA	1
Sacramento-Yolo, CA	1.7
San Diego, CA	2.8
San Francisco-Oakland-San Jose, CA	6.9
San Joaquin Valley, CA	3.2
St. Louis, MO-IL	2.6
Ventura County, CA	0.7
Washington, DC-Baltimore, DC, MD, VA MSA	7.4
20 Areas	54.2

Table II.A-6. Areas and 1999 Populations at Risk of Exceeding the Ozone Standard between 2007 and 2030

Areas with Pre-2007 Attainment Dates and Recent Concentrations within 10 Percent of an Exceedance, But With No Recent History of Nonattainment.	
Barnstable-Yarmouth, MA	0.2
Benton Harbor, MI	0.2
Biloxi-Gulfport-Pascagoula, MS MSA	0.4
Charleston, WV MSA	0.3
Cincinnati-Hamilton, OH-KY-IN	2.0
Cleveland-Akron, OH CMSA	2.9
Grand Rapids-Muskegon-Holland, MI MSA	1.1
Houma, LA	0.2
Lake Charles, LA	0.2
New Orleans, LA MSA	1.3
Norfolk-Virginia Beach-Newport News, VA-NC MSA	1.6
Orlando, FL MSA	1.5
Pensacola, FL MSA	0.4
Providence-Fall River-Warwick, RI-MA	1.1
Tampa-St. Petersburg-Clearwater, FL MSA	2.3
15 areas	15.7
Total Areas: 45	Population: 128

e. Public Health and Welfare Concerns from Prolonged and Repeated Exposures to Ozone

There exists a large body of scientific literature regarding health and welfare effects of ozone. Initially, research indicates that there were harmful effects resulting from peak ozone levels (e.g., one-hour concentrations above 0.125 ppm). However, in recent years, research has shown that harmful effects can occur from much lower, sustained levels of exposure. Studies of prolonged exposures, those lasting about 7 hours, showed health effects from exposures to ozone concentrations as low as 0.08 ppm. Prolonged and repeated exposures to ozone at these levels are common in areas that do not attain the 1-hour NAAQS, and also occur in areas where ambient concentrations of ozone are in compliance with the 1-hour NAAQS. Thus, adverse health effects from this type of ozone exposure can reasonably be anticipated to occur in the future in the absence of this rule. Adverse welfare effects can also be anticipated, primarily from damage to vegetation at ozone levels below peak levels.

i. Health and Welfare Effects

Studies of acute health effects from ozone have reported ozone exposure to cause or be statistically associated with transient pulmonary function responses, transient respiratory symptoms, effects on exercise performance, increased airway responsiveness, increased susceptibility to respiratory infection, increased hospital and emergency room visits, and transient pulmonary respiratory inflammation. Such acute health effects have been observed following prolonged exposures at moderate levels of exertion at concentrations of ozone as low as 0.08 ppm, the lowest concentration tested. The effects are more pronounced as concentrations increase, affecting more subjects or having a greater effect on a given subject in terms of functional changes or symptoms. A detailed summary and discussion of the large body of ozone health effects research may be found in Chapters 6 through 9 (Volume 3) of the 1996 Criteria Document for ozone.¹¹

The following is a brief summary focusing on studies on the effects of exposures to concentrations of ozone just at and below peak ozone concentrations. Tables II.A-7 through II.A-11 of this section are excerpted from the 1996 Criteria Document, with only studies that used peak ozone concentrations or below retained.

It has long been established by exposure chamber studies that single, short-term (1 to 3 hour) exposures to ozone concentrations at or above peak levels produce a variety of respiratory function effects in exposed subjects. Tables II.A-7 and II.A-8 summarize these studies, for healthy and diseased subjects, and also indicate that equally short-term exposures to concentrations below peak levels have not shown these effects. More recent studies have sought to investigate whether similar effects occur following longer exposures to lower levels of ozone. These studies are summarized here in Tables II.A-9 and II.A-10. Exposures of 6.6 hours to ozone concentrations of 0.08, 0.10, and 0.12 ppm were used in these chamber exposures studies, and are reported to cause decrements in lung function (reduced ability to take a deep breath), increased respiratory symptoms (cough, shortness of breath, pain upon deep inspiration), increased airway responsiveness (an indication that airways are predisposed to bronchoconstriction, which is characteristic of asthma), and increased airway inflammation in adults. The effects are more pronounced as concentrations increase, affecting more subjects or having a greater effect on a given subject in terms of functional changes or symptoms. Earlier studies found these effects in heavily exercising adults exposed to ozone on a short-term basis, but the level of exertion involved was high enough to be unusual among people conducting their normal activities. The more recent studies with 6.6 hour exposures at 0.08 and 0.10 ppm observed these functional changes and symptoms when subjects were exerting themselves at only moderate levels. This means that much of the population could experience these effects from ambient concentrations while conducting their normal activities at moderate exertion levels.

With regard to chronic health effects, the collective data from these chamber studies have many ambiguities, but provide suggestive evidence of chronic effects in humans. Table II.A-11 summarizes studies associating a single prolonged exposure to ozone at 0.08 and 0.10 ppm with lung inflammation. There is a biologically plausible basis for considering the possibility that repeated inflammation associated with exposure to ozone over a lifetime, as can occur with exposure to 8-hour ozone levels as low as 0.08 ppm, may result in sufficient damage to respiratory tissue such that individuals later in life may experience a reduced quality of life, although such relationships remain highly uncertain.

A number of “summer camp” studies of children and adolescents, and other types of epidemiological studies involving exposure to ambient concentrations of ozone, confirm that ozone concentrations are correlated with lung function changes, as indicated by the chamber studies. The studies are not summarized in table form here. Changes reported at low ozone concentrations in these studies are comparable to those observed in the chamber studies, although comparisons are difficult because of differences in experimental design and analytical approach. Studies published since 1986 have supported a direct association between ambient ozone/oxidant concentrations and acute respiratory morbidity in asthmatics, although it is difficult to clearly differentiate the independent effects of ozone from those of copollutants. Conclusions from the field studies on asthmatics are based on observations over a range of ozone exposures extending below the 0.12 ppm level of the 1-hour NAAQS.

Over 20 epidemiology studies of aggregate populations have investigated the relationship between ozone concentrations and hospital admissions/ hospital visits. The studies are not summarized in table form here. Significant associations are seen between ozone and hospital admissions/visits at exposures below 0.12 ppm 1-hour daily maximum ozone.

Ozone also has many welfare effects, with damage to plants being of most concern. Plant damage affects crop yields, forestry production, and ornamentals. The adverse effect of ozone on forests and other natural vegetation can in turn cause damage to associated ecosystems, with additional resulting economic losses. Ozone concentrations of 0.10 ppm can be phytotoxic to a large number of plant species, and can produce acute injury and reduced crop yield and biomass production. Ozone concentrations within the range of 0.05 to 0.10 ppm have the potential over a longer duration of creating chronic stress on vegetation that can result in reduced plant growth and yield, shifts in competitive advantages in mixed populations, decreased vigor, and injury. Ozone effects on vegetation are presented in more detail in Chapter 5, Volume II of the 1996 Criteria Document.

Table II.A-7. Controlled Exposure of Healthy Human Subjects to Ozone *

<i>Ozone Concentration</i>		<i>Exposure Duration and Activity</i>	<i>Exposure Conditions</i>	<i>Number and Gender of Subjects</i>	<i>Subject Characteristics</i>	<i>Observed Effect(s)</i>	<i>Reference</i>
<i>ppm</i>	<i>μg/m³</i>						
<i>Healthy Exercising Adult Subjects</i>							
0.08	157	2 h IE	Tdb = 32 °C	24 M	Young,	No significant changes in pulmonary	Linn et al. (1986)
0.10	196	(4 × 15 min	RH = 38%		healthy adults,	function measurements.	
0.12	235	at $\dot{V}_E =$			18 to		
0.14	274	68 L/min)			33 years old		
0.16	314						
0.12	235	1 h	Tdb = 23 to	10 M	10 highly	Decrease in FVC and FEV ₁ for 0.18- and	Schelegle and Adams
0.18	353	competitive	26 °C		trained	0.24-ppm O ₃ exposure compared with FA	(1986)
0.24	470	simulation	RH = 45 to		competitive	exposure; decrease in exercise time for	
		exposures at	60%		cyclists, 19 to	subjects unable to complete the competitive	
		mean $\dot{V}_E =$			29 years old	simulation at 0.18 and 0.24 ppm O ₃ ,	
		87 L/min				respectively.	
0.12	235	2.5 h IE	Tdb = 22 °C	20 M	Young,	Significant decrease in FVC, FEV ₁ , and	McDonnell et al.
0.18	353	(4 × 15 min	RH = 40%	22 M	healthy adults,	FEF _{25-75%} at 0.12 ppm O ₃ ; decrease in V _T	(1983)
0.24	470	treadmill		20 M	18 to	and increase in f and SR _{aw} at 0.24 ppm O ₃ .	
0.30	588	exercise		21 M	30 years old		
0.40	784	[$\dot{V}_E =$		20 M			
		65 L/min])		29 M			

Table II.A-7. Controlled Exposure of Healthy Human Subjects to Ozone *

0.12	235	2 × 2.5 h IE	Tdb = 22 °C	8 M	Young,	Pulmonary function variables SR _{aw} and \dot{V}_E were not significantly different in repeat exposures, indicating that the response to 0.18 ppm O ₃ or higher is reproducible.	McDonnell et al. (1985b)
0.18	353	(4 × 15 min	RH = 40%	8 M	healthy adults,		
0.24	470	treadmill		5 M	18 to		
0.30	588	exercise		5 M	30 years old		
0.40	784	[\dot{V}_E = 35 L/min/m ² BSA]).		6 M			
		Exposure separated by 48 ± 30 days and 301 ± 77 days					
0.12	235	2 × 2.5 h IE	Tdb = 22 °C	290 M	Young,	O ₃ concentration and age predicted FEV ₁ decrements; it was concluded that age is a significant predictor of response (older subjects being less responsive to O ₃).	McDonnell et al. (1993)
0.18	353	(4 × 15 min	RH = 40%		healthy adults,		
0.24	470	treadmill			18 to		
0.30	588	exercise			32 years old		
0.40	784	[\dot{V}_E = 35 L/min/m ² BSA])					
0.12	235	2.5 h IE	Tdb = 22 °C	17 WM/15 BM/15	Young,	Decreases in FEV ₁ for all levels of O ₃ as compared with FA; increase in SR _{aw} with 0.18 ppm O ₃ and greater compared with FA; black men and women had larger FEV ₁ decrements than white men, and black men had larger FEV ₁ decrements than white women.	Seal et al. (1993)
0.18	353	(4 × 15 min	RH = 40%	WF/ 15BF	healthy whites		
0.24	470	treadmill		15 WM/15 BM/15	and blacks, 18		
0.30	588	exercise		WF/ 16BF	to 35 years old		
0.40	784	[\dot{V}_E = 25 L/min/m ² BSA])		15 WM/17 BM/17 WF/ 15BF 16 WM/15 BM/17 WF/ 16BF 15 WM/15 BM/15 WF/ 15BF 15 WM/15 BM/15 WF/ 15BF			

Table II.A-7. Controlled Exposure of Healthy Human Subjects to Ozone *

0.12	235	1 h CE	Tdb = 31 °C	15 M	Highly trained	Decrease in $\dot{V}_{E_{max}}$, $\dot{V}O_{2max}$, V_{Tmax} , work load, ride time, FVC, and FEV ₁ with 0.20 ppm O ₃ exposure during maximal exercise conditions, but not significant with 0.12 ppm O ₃ exposure, as compared to FA exposure.	Gong et al. (1986)
0.20	392	(mean \dot{V}_E = 89 L/min)		2 F	competitive cyclists, 19 to 30 years old		
0.10	196	2 h IE	Tdb = 22 °C	20 M	Young,	FVC, FEV ₁ , FEF _{25-75%} , SG _{aw} , IC, and TLC all decreased with (1) increasing O ₃ concentration, and (2) increasing time of exposure; threshold for response was above 0.10 ppm but below 0.15 ppm O ₃ .	Kulle et al. (1985)
0.15	294	(4 × 14 min	RH = 50%		healthy NS,		
0.20	392	treadmill at			25.3 ± 4.1		
0.25	490	mean \dot{V}_E = 70.2 L/min)			(SD) years old		

* See Appendix A of the 1996 Ozone Criteria Document for abbreviations and acronyms.

Table II.A-8. Ozone Exposure in Subjects with Preexisting Disease

Ozone Concentration ppm $\mu\text{g}/\text{m}^3$	Exposure Duration and Activity	Exposure Condition	Number and Gender of Subjects	Subject Characteristics	Observed Effect(s)	Reference
Subjects with Chronic Obstructive Pulmonary Disease						
0.12 236	1 h IE (2 × 15 min light bicycle ergometry)	Tdb = 25 °C RH = 50%	18 M, 7 F	8 smokers, 14 ex-smokers, 3 nonsmokers; FEV ₁ /FVC = 32 to 66%	No significant changes in pulmonary function measurements; small significant decrease in arterial O ₂ saturation.	Linn et al. (1982a)
Adult Subjects with Asthma						
0.10 196 0.25 490 0.40 784	1 h light IE (2 × 15 min on treadmill, $\dot{V}_E = 27$ L/min)	Tdb = 21 °C RH = 40%	12 M, 9 F, 19 to 40 years old	Stable mild asthmatics with FEV ₁ > 70% and methacholine responsiveness	No significant differences in FEV ₁ or FVC were observed for 0.10 and 0.25 ppm O ₃ -FA exposures or postexposure exercise challenge; 12 subjects exposed to 0.40 ppm O ₃ showed significant reduction in FEV ₁ .	Weymer et al. (1994)
0.12 236	1 h rest	NA	7 M, 8 F	Never smoked, mild stable asthmatics with exercise-induced asthma	Exposure to 0.12 ppm O ₃ did not affect pulmonary function. Preexposure to 0.12 ppm O ₃ at rest did not affect the magnitude or time course of exercise-induced bronchoconstriction.	Fernandes et al. (1994)
0.12 236	0.75 h IE ($\dot{V}_E = 30$ L/min (15 min rest, 15 min exercise, 15 min rest) followed by 15 min exercise inhaling 0.10 ppm SO ₂)	Tdb = 22 °C RH = 75%	8 M, 5 F, 12 to 18 years old	Asthmatics classified on basis of positive clinical history and methacholine challenge. Asymptomatic at time of study.	Filtered air followed by SO ₂ and O ₃ alone did not cause significant changes in pulmonary function. Ozone followed by SO ₂ resulted in significant decrease in FEV ₁ (8%) and $\dot{V}_{\text{max}50\%}$ (15%) and a significant increase in R _T (19%).	Koenig et al. (1990)

Table II.A-8. Ozone Exposure in Subjects with Preexisting Disease

0.12	236	1.5 h IE, $\dot{V}_E =$ 25 L/min	Tdb = 22 °C RH = 65%	4 M, 4 F (nonasthmatics); 18 to 35 years old; 5 M, 5 F (asthmatics); 18 to 41 years old	Physician- diagnosed asthma confirmed with methacholine challenge test. All nonsmokers and asymptomatic at time of study. Nine were atopic.	No significant changes in pulmonary and nasal function measurements in either asthmatics or nonasthmatics. Significant increase in nasal lavage white cell count and epithelial cell following O ₃ exposure in asthmatics only.	McBride et al. (1994)
0.12	236	6.5 h/day IE (6 × 50 min) (2 days of exposure), \dot{V}_E = 28 L/min (asthmatic), $\dot{V}_E = 31$ L/min (healthy)	NA	8 M, 7 F (nonasthmatics); 22 to 41 years old; 13 M, 17 F (asthmatics); 18 to 50 years old	Asthmatics classified on basis of positive clinical history, previous physician diagnosis, and low PD ₂₀ . Mild to severe asthmatics.	Significant increase in bronchial reactivity to methacholine in both asthmatics and nonasthmatics. FEV ₁ decreased 8.6% in asthmatics and 1.7% in nonasthmatics, with difference not being significant.	Linn et al. (1994)
0.12	236	1 h rest	NA	4 M, 3 F, 21 to 64 years old	Mild, stable asthma	Increase in bronchial responsiveness to allergen; no change in baseline airway function.	Molfino et al. (1991)
<i>Adolescent Subjects with Asthma</i>							
0.12	235	1 h rest	Tdb = 22 °C RH ≥ 75%	4 M, 6 F (normals), 13 to 18 years old; 4 M, 6 F (asthmatics), 11 to 18 years old	Asthmatics had a history of atopic extrinsic asthma and exercise- induced bronchospasm	Decrease in FRC with O ₃ exposure in asthmatics; no consistent significant changes in pulmonary functional parameters in either group or between groups.	Koenig et al. (1985)

Table II.A-8. Ozone Exposure in Subjects with Preexisting Disease

0.12	235	1 h IE (2 × 15 min treadmill walking at mean $\dot{V}_E =$ 32.5 L/min)	Tdb = 22 °C RH ≥ 75%	5 M, 8 F (normals), 12 to 17 years old; 9 M, 3 F (asthmatics), 12 to 17 years old	Asthmatics selected from a clinical practice and had exercise- induced bronchospasm	Decrease in maximal flow at 50% of FVC in asthmatics with O ₃ exposure compared to FA; no significant changes with combined O ₃ -NO ₂ exposure.	Koenig et al. (1988)
0.12	235	40 min IE	NA	4 M, 9 F (normals), 14 to 19 years old;	Asthmatics had allergic asthma, positive responses to methacholine, and exercise- induced bronchospasm	Decrease in FEV ₁ and increase in R _T in normals and asthmatics with 0.12 and 0.18 ppm O ₃ exposure compared to FA; no consistent differences between normals and asthmatics.	Koenig et al. (1987)
0.18	353	(1 × 10 min treadmill walking at mean $\dot{V}_E =$ 32.5 L/min)		8 M, 8 F (asthmatics), 12 to 19 years old			

Table II.A-9. Pulmonary Function Effects After Prolonged Exposures to Ozone

<i>Ozone Concentration</i> ppm	<i>$\mu\text{g}/\text{m}^3$</i>	<i>Exposure</i> <i>Duration and Activity</i>	<i>Exposure</i> <i>Conditions</i>	<i>Number and</i> <i>Gender of</i> <i>Subjects</i>	<i>Subject</i> <i>Character-istics</i>	<i>Observed Effect(s)</i>	<i>Reference</i>
0.08	157	6.6 h	18 °C	22 M	Healthy NS, 18 to 33 years old	FVC and FEV ₁ decreased throughout the exposure; FEV ₁ decrease at end exposure was 7.0, 7.0, and 12.3%, respectively. FEV ₁ change >15% occurred in 3, 5, and 9 subjects at 0.08, 0.10, and 0.12 ppm, respectively. Methacholine responsiveness increased by 56, 89, and 121%, respectively.	Horstman et al. (1990)
0.10	196	IE (6 × 50 min)	40% RH				
0.12	235	$\dot{V}_E \approx 39$ L/min					
		See Horstman et al. (1990) and Folinsbee et al. (1988)				A lognormal model was fitted to FEV ₁ data. Model parameters indicate O ₃ concentration had greater effect than \dot{V}_E or duration (estimated exponent for [O ₃] $\approx 4/3$).	Larsen et al. (1991)
0.08	157	6.6 h	18 °C	38 M	Healthy NS, mean age 25 years old	FEV ₁ decreased 8.4% at 0.08 ppm and 11.4% at 0.10 ppm. Symptoms of cough, PDI, and SB increased with O ₃ exposure.	McDonnell et al. (1991)
0.10	196	IE (6 × 50 min) $\dot{V}_E = 40$ L/min	40% RH				
0.08	157	6.6 h IE (6 × 50 min) $\dot{V}_E = 35$ to 38 L/min (1 day of air, 2 days of O ₃)	25 °C 48% RH	5 F, 6 M	Healthy NS, 30 to 45 years old	FVC decreased 2.1%, FEV ₁ decreased 2.2% on first day of O ₃ exposure; no change on second O ₃ day.	Horvath et al. (1991)

Table II.A-9. Pulmonary Function Effects After Prolonged Exposures to Ozone

0.12	235	6.6 h IE (6 × 50 min) $\dot{V}_E = 42.6$ L/min	18 °C 40% RH (1 exposure to clean air; 1 exposure to O ₃)	10 M	Healthy NS, 18 to 33 years old	FEV ₁ decreased by 13% after 6.6 h. FVC dropped 8.3%. Cough and PDI increased with O ₃ exposure. Airway responsiveness to methacholine doubled after O ₃ exposure.	Folinsbee et al. (1988)
0.12	235	6.5 h/day IE (6 × 50 min) (2 days of exposure) $\dot{V}_E = 28$ L/min (asthmatic) $\dot{V}_E = 31$ L/min (healthy)	21 °C 50% RH	15 (8 M, 7 F) 30 (13 M, 17 F)	Healthy NS, 22 to 41 years old Asthmatic NS, 18 to 50 years old	Bronchial reactivity to methacholine increased with O ₃ exposure in healthy subjects. FEV ₁ decreased 2% (pre- to postexposure) in healthy subjects and 7.8% in asthmatics. Responses were generally less on the second day. Two healthy subjects and four asthmatics had FEV ₁ decreases >10%.	Linn et al. (1994)
0.12	235	6.6 h IE (6 × 50 min) $\dot{V}_E = 38.8$ L/min	18 °C 40% RH (5 consecutive days of exposure to O ₃ , 1 day exposure to CA)	17 M	Healthy NS, mean age 25 ± 4 years old	FEV ₁ decreased by 12.8, 8.7, 2.5, and 0.6 and increased by 0.2 on Days 1 to 5 of O ₃ exposure, respectively. Methacholine airway responsiveness increased by >100% on all exposure days. Symptoms increased on the first O ₃ day, but were absent on the last 3 exposure days.	Folinsbee et al. (1994)

Table II.A-9. Pulmonary Function Effects After Prolonged Exposures to Ozone

(a) 0.12 (b) Varied from 0.0 to 0.24 (increased by 0.06 ppm/h then decreased by 0.06 ppm/h)	235	8 h IE (8 × 30 min) $\dot{V}_E = 40$ L/min	22 °C 40% RH <3 $\mu\text{g}/\text{m}^3$ TSP	23 M	Healthy NS, 20 to 35 years old	(a) FEV ₁ decreased 5% by 6 h and remained at this level through 8 h. (b) FEV ₁ change mirrored O ₃ concentration change with a lag time of ≈ 2 h. Max decrease of 10.2% after 6 h. FEV ₁ change was reduced in last 2 h of exposure.	Hazucha et al. (1992)
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* See Appendix A of the 1996 Ozone Criteria Document for abbreviations and acronyms.

Table II.A-10. Increased Airway Responsiveness Following Ozone Exposures *

Ozone Concentration **		Exposure Duration and Activity	Exposure Conditions	Number and Gender of Subjects	Subject Characteristics	Observed Effect(s)	Reference
ppm	$\mu\text{g}/\text{m}^3$						
0.08	157	6.6 h	18 °C	22 M	Healthy NS,	33, 47, and 55% decreases in cumulative dose of methacholine required to produce a 100% increase in SR_{aw} after exposure to O_3 at 0.08, 0.10, and 0.12 ppm, respectively.	Horstman et al. (1990)
0.10	196	IE at ≈ 39 L/min	40% RH	18 to 32 years old	Healthy NS,		
0.12	235						
0.10	196	2 h	NA	14	Health NS,	Increased airway responsiveness to methacholine immediately after exposure at the two highest concentrations of O_3 .	König et al. (1980)
0.32	627	1 h at $\dot{V}_E = 89$ L/min followed by 3 to 4 min at ≈ 150 L/min	31 °C	15 M, 2 F	Elite cyclists, 19 to 30 years old		
1.00	1,960						
0.12	235	6.6 h with IE at ≈ 25 L/min/m ² BSA	35% RH	10 M	Healthy NS, 18 to 33 years old	Greater than 20% increase in histamine responsiveness in one subject at 0.12 ppm O_3 and in nine subjects at 0.20 ppm O_3 .	Gong et al. (1986)
0.20	392						
0.12	235	45 min in first atmosphere and 15 min in second IE	75% RH	8 M, 5 F	Asthmatic, 12 to 18 years old	Approximate doubling of mean methacholine responsiveness after exposure. On an individual basis, no relationship between O_3 -induced changes in airway responsiveness and FEV_1 or FVC .	Folinsbee et al. (1988)
0.12 ppm O_3 -100 ppb SO_2	0.12 ppm O_3 -0.12 ppm O_3 -100 ppb SO_2						
Air-antigen	0.12 ppm O_3 -antigen	1 h at rest	NA	4 M, 3 F	Asthmatic, 21 to 64 years old	Greater declines in FEV_1 and $\dot{V}_{\text{max}50\%}$ and greater increase in respiratory resistance after O_3 - SO_2 than after O_3 - O_3 or air- SO_2 .	Koenig et al. (1990)
						Increased bronchoconstrictor response to inhaled ragweed or grass after O_3 exposure compared to air.	Molfino et al. (1991)

* See Appendix A of the 1996 Ozone Criteria Document for abbreviations and acronyms.

Table II.A-11. Bronchoalveolar Lavage Studies of Inflammatory Effects from Controlled Human Exposure to Ozone

<i>Ozone Concentration^b</i>		<i>Exposure Duration</i>	<i>Activity Level (V_E)</i>	<i>Number and Gender of Subjects</i>	<i>Observed Effect(s)</i>	<i>Reference</i>
0.08 ppm	157 $\mu\text{g}/\text{m}^3$	6.6 h	IE (40 L/min)	18 M,	BAL fluid 18 h after exposure to 0.1 ppm O ₃ had significant increases in PMNs, protein, PGE ₂ , fibronectin, IL-6, lactate dehydrogenase, and α -1 antitrypsin compared with the same subjects exposed to FA. Similar but smaller increases in all mediators after exposure to 0.08 ppm O ₃ except for protein and fibronectin. Decreased phagocytosis of yeast by alveolar macrophages was noted at both concentrations.	Devlin et al. (1990, 1991)
0.10	196	six 50-min exercise periods + 10 min rest; 35 min lunch	18 to 35 years old	Koren et al. (1991)		

ii. Ozone Concentrations

This section summarizes the results of analyses of model-adjusted ozone air quality concentrations and the anticipated air quality impact of reductions in emissions expected to result from implementation of the heavy duty engine and vehicle standards and highway diesel fuel sulfur control requirements. Specifically, it provides information on the number of people estimated to live in metropolitan counties in which ozone monitors are predicted to repeatedly experience certain levels of ozone of potential concern over prolonged periods, i.e., 8-hours.

Heavy-duty vehicles contribute a substantial fraction of ozone precursors in any metropolitan area. Available health studies (summarized above) have indicated health effects (e.g., lung function decrements, respiratory symptoms, and pulmonary inflammation) at ozone concentrations between 0.08 ppm and 0.12 ppm over prolonged exposures (6.6 hours in most chamber studies). An 8-hour averaging period was chosen as a convenient and appropriate metric for describing current and future ozone patterns relevant to this concentration range. Another important metric is the number of days with ozone levels between 0.08 and 0.12 ppm because repeated exposure to ozone in this concentration range may be associated with long term health effects related to pulmonary inflammation.

To provide a quantitative estimate of the number of people anticipated to reside in areas in which ozone concentrations are predicted to experience multiple days with 8-hour ozone in the range of 0.08 to 0.12 ppm and higher, we performed regional modeling for 6 different scenarios (1996 base, 2007 base, 2020 base and control, 2030 base and control) for the eastern United States. This modeling is further described in section A.2.6 "Photochemical Ozone Modeling." Our analysis relies on projected county-level population from the U.S. Department of Census for the period representing each year analyzed.

For each of the counties analyzed, we determined the number of days for periods on which the highest model-adjusted 8-hour concentration at any monitor in the county was predicted, for example, to be between 0.08 and 0.12 ppm (after rounding from 3 decimal places). We then grouped the counties which had days with ozone in this range according to the number of days this was predicted to happen, and summed their projected populations. We repeated this for ozone ranges of 0.09 to 0.12 ppm, 0.10 to 0.12 ppm, 0.11 to 0.12 ppm and greater than or equal to 0.12 ppm.

In the 2007 base case (i.e., before the application of emission reductions resulting from this rule), we estimated that 116 million, or 93 percent of the total population considered in this analysis, are predicted to live in areas with at least 2 days with model-adjusted 8-hour average concentrations of 0.08 ppm or higher. The number of people involved is predicted to diminish as the lower end of the concentration range increases or as the number of days predicted to experience such peak 8-hour average concentrations increases. The number of people predicted

to live in areas with at least 2 days with model-adjusted 8-hour average concentrations of 0.08 ppm or higher is estimated to increase in the 2020 base case to 122 million people, although this is estimated to represent a smaller percentage (87 percent) of the total projected population considered in the analysis. However, both the number of people (139 million) and the relative percentage (91 percent) of the total population considered in the analysis is projected to grow in the 2030 base case.

3. Particulate Matter

a. Health and Welfare Effects of Ambient Particulate Matter

Particulate matter (PM) represents a broad class of chemically and physically diverse substances that exist as discrete particles (liquid droplets or solids) over a wide range of sizes. Coarse PM are those particles which have a diameter in the range of 2.5 to 10 microns, and fine particles are those particles which have a diameter less than 2.5 microns. Typically, PM is also classified as PM₁₀ (all particles less than 10 microns) or PM_{2.5} (all particles less than 2.5 microns). Human-generated sources of particles include a variety of stationary sources (including power generating plants, industrial operations, manufacturing plants, waste disposal) and mobile sources (light- and heavy-duty on-road vehicles, and off-highway vehicles such as construction, farming, industrial, locomotives, marine vessels and other sources). Particles may be emitted directly to the atmosphere (primary particles) or may be formed by transformations of gaseous emissions of sulfur dioxide, nitrogen oxides or volatile organic compounds (secondary particles). Secondary PM is dominated by sulfate in the eastern U.S. and nitrate in the western U.S.¹² Essentially all (>90 percent) of the direct mobile source PM emissions and their secondary formation products are in the fine PM size range. Mobile sources can reasonably be estimated to contribute to ambient secondary nitrate and sulfate PM in proportion to their contribution to total NO_x and SO_x emissions.

The chemical and physical properties of PM vary greatly with time, region, meteorology, and source category, thus complicating the assessment of health and welfare effects. At elevated concentrations, particulate matter can adversely affect human health, visibility, and materials. Components of particulate matter (e.g., sulfuric or nitric acid) also contribute to acid deposition, nitrification of surface soils and water and eutrophication of surface water as will be discussed below.

Key EPA findings regarding the health risks posed by ambient particulate matter can be found in the Air Quality Criteria for Particulate Matter and are summarized as follows:

- a. Health risks posed by inhaled particles are affected both by the penetration and deposition of particles in the various regions of the respiratory tract, and by the biological responses to these deposited materials.

- b. The risks of adverse effects associated with deposition of ambient particles in the thorax (tracheobronchial and alveolar regions of the respiratory tract) are markedly greater than for deposition in the extrathoracic (head) region. Maximum particle penetration to the thoracic regions occurs during oronasal or mouth breathing.
- c. The key health effects categories associated with PM include premature death; aggravation of respiratory and cardiovascular disease, as indicated by increased hospital admissions and emergency room visits, school absences, work loss days, and restricted activity days; changes in lung function and increased respiratory symptoms; changes to lung tissues and structure; and altered respiratory defense mechanisms. Most of these effects have been consistently associated with ambient PM concentrations, which have been used as a measure of population exposure, in a large number of community epidemiological studies. Additional information and insights on these effects are provided by studies of animal toxicology and controlled human exposures to various constituents of PM conducted at higher than ambient concentrations. Although mechanisms by which particles cause effects are not well known, there is general agreement that the cardio-respiratory system is the major target of PM effects.
- d. Based on a qualitative assessment of the epidemiological evidence of effects associated with PM for populations that appear to be at greatest risk with respect to particular health endpoints, we have concluded the following with respect to sensitive populations:
1. Individuals with respiratory disease (e.g., chronic obstructive pulmonary disease, acute bronchitis) and cardiovascular disease (e.g., ischemic heart disease) are at greater risk of premature mortality and hospitalization due to exposure to ambient PM.
 2. Individuals with infectious respiratory disease (e.g., pneumonia) are at greater risk of premature mortality and morbidity (e.g., hospitalization, aggravation of respiratory symptoms) due to exposure to ambient PM. Also, exposure to PM may increase individuals' susceptibility to respiratory infections.
 3. Elderly individuals are also at greater risk of premature mortality and hospitalization for cardiopulmonary problems due to exposure to ambient PM.
 4. Children are at greater risk of increased respiratory symptoms and decreased lung function due to exposure to ambient PM.
 5. Asthmatic individuals are at risk of exacerbation of symptoms associated with asthma, and increased need for medical attention, due to exposure to PM.

- e. There are fundamental physical and chemical differences between fine and coarse fraction particles. The fine fraction contains acid aerosols, sulfates, nitrates, transition metals, diesel exhaust particles, and ultra fine particles and the coarse fraction typically contains high mineral concentrations, silica and resuspended dust. It is reasonable to expect that differences may exist in both the nature of potential effects elicited by coarse and fine PM and the relative concentrations required to produce such effects. Both fine and coarse particles can accumulate in the respiratory system. Exposure to coarse fraction particles is primarily associated with the aggravation of respiratory conditions such as asthma. Fine particles are most closely associated with health effects such as premature death or hospital admissions, and for cardiopulmonary diseases.

With respect to welfare or secondary effects, fine particles have been clearly associated with the impairment of visibility over urban areas and large multi-State regions. Fine particles, or major constituents thereof, also are implicated in materials damage, soiling and acid deposition. Coarse fraction particles contribute to soiling and materials damage.

Particulate pollution is a problem affecting urban and non-urban localities in all regions of the United States. Manmade emissions that contribute to airborne particulate matter (listed above) result principally from combustion sources (stationary and mobile sources) and fugitive emissions from industrial process and non-industrial processes (such as roadway dust from paved and unpaved roads, wind erosion from cropland, construction, etc.). Natural sources also contribute to particulate matter in the atmosphere and include sources such as wind erosion of geological material, sea spray, volcanic emissions, biogenic emanation (e.g., pollen from plants, fungal spores), and wild fires. Emission inventories for the relative contribution of diesel PM to total ambient PM will be discussed below.

Secondary diesel PM includes particles containing sulfuric acid, nitric acid and organic compounds of diesel exhaust origin. Sulfur dioxide (SO_2) and nitrogen oxides (primarily nitric oxide, or NO), are emitted from diesel engines. Sulfur dioxide is converted to sulfuric acid in the presence of oxidizing reactants and water vapor to form (H_2SO_4) droplets which are less than 1 μm in diameter. Because SO_2 is soluble in water, it is scavenged by fog, cloud water, and raindrops. Sulfur emitted from diesel engines is predominantly (~98 percent) in the form of SO_2 , a portion of which will form sulfate aerosols by the reaction described above. Off-road equipment, typically use fuel containing 3300 ppm sulfur, and therefore emit more SO_2 than on-road diesel engines which use fuels currently containing an average of 340 ppm sulfur. We estimate that mobile sources are responsible for about seven percent of nationwide SO_2 emissions with diesel engines contributing 80 percent of the mobile source total (the majority of the diesel SO_2 emissions originate from off-highway engines).¹³ The portion of this SO_2 which is subsequently converted to sulfuric acid will vary regionally and, especially in the eastern U.S., the contribution of diesel emissions will be minimal.

Nitric oxide (NO) is also oxidized in the atmosphere to form NO₂ and particulate nitrate (nitric acid and ammonium nitrate primarily). Organic aerosols are also formed from atmospheric transformation of hydrocarbons emitted in the gaseous phase from diesel engines. Little research has been conducted to characterize the contribution of diesel exhaust to secondary organic particulates in the ambient air. Some studies suggest that up to 38 percent of the organic aerosol in an urban environment can be secondary in origin, a portion of which would come from diesel exhaust.¹⁴ In a recent modeling study by Kleeman and Cass, 8.96 µg/m³ PM_{2.5} (67 percent of the diesel PM_{2.5} mass) at Riverside, CA was attributed to secondary formation from direct diesel emissions.¹⁵ A portion of the secondary PM_{2.5} was attributed to primary emissions of hydrocarbons (1 percent). The majority (70 percent) of the secondary diesel PM_{2.5} at Riverside was attributed to nitrate formation.

The sources, ambient concentration, and chemical and physical properties of PM₁₀ vary greatly with time, region, meteorology, and source category. A first step in developing a plan to attain the PM₁₀ NAAQS is to disaggregate ambient PM₁₀ into the basic categories of sulfate, nitrate, carbonaceous, and crustal, and then determine the major contributors to each category based on knowledge of local and upwind emission sources. Following this approach, SIP strategies to reduce ambient PM concentrations have generally focused on controlling fugitive dust from natural soil and soil disturbed by human activity, paving dirt roads and controlling of soil on paved roads, reducing emissions from residential wood combustion, and controlling major stationary sources of PM₁₀ where applicable. The control programs to reduce stationary, area, and mobile source SO₂, NO_x, and VOCs to achieve attainment with the sulfur dioxide and ozone NAAQS also have contributed to reductions in the fine fraction of PM₁₀ concentrations. In addition, the EPA standards for PM emissions from highway and off-highway engines are contributing to reducing PM₁₀ concentrations. As result of all these efforts, in the last ten years, there has been a downward trend in PM₁₀ concentrations, with a leveling off in the later years.¹⁶

Heavy-duty vehicles contribute to fine particle formation through a number of pollutants. The chemical composition of PM fine varies by region of the country (see Table II.A-12). Sulfate plays a major role in the composition of fine particulate across the country, but typically makes up over half the fine particles found in the Eastern United States. Organic carbon accounts for a large portion of fine particle mass, with a slightly higher fraction in the west. Diesel engines are the principle source of elemental carbon, which makes up about 5-6 percent of particle mass.

Table II.A-12. Percent Contribution to PM_{2.5} by Component, 1998 ^P

	East	West
Sulfate	56	33
Elemental Carbon	5	6
Organic Carbon	27	36
Nitrate	5	8
Crustal Material	7	17

Nationally, nitrate plays a relatively small roles in the make up of fine particles, but it plays a far larger role in southern California. Ammonium nitrate – formed secondarily from NO_x and ammonia emissions -- is one of the most significant components of particulate matter pollution in California. During some of the worst episodes of elevated particle levels in the South Coast, ammonium nitrate can account about 65-75 percent of the PM_{2.5} mass.⁹ Reducing ammonium nitrate through controls on NO_x sources is a critical part of California’s particulate matter strategy. Nationally, the standards finalized in this rule will significantly reduce HDV emissions of SO_x, NO_x, VOCs and elemental carbon, and thus contribute to reductions in ambient concentrations of PM₁₀ and PM_{2.5}.

i. Current PM₁₀ Nonattainment

The most recent PM₁₀ monitoring data indicates that 14 designated PM₁₀ nonattainment areas with a projected population of 23 million violated the PM₁₀ NAAQS in the period 1997-1999. Table II.A-13 lists the 14 areas, and also indicates the PM₁₀ nonattainment classification, and 1999 projected population for each PM₁₀ nonattainment area. The projected population in

^P National Air Quality and Emissions Trends Report, 1998, EPA 454/R-00-003, March, 2000.

⁹ Southern California 1997 PM₁₀ Air Quality Management Plan.

1999 was based on 1990 population figures which were then increased by the amount of population growth in the county from 1990 to 1999.

Table II.A-13. PM₁₀ Nonattainment Areas Violating the PM₁₀ NAAQS in 1997- 1999

Nonattainment Area or County	1999 Population (projected, in millions)
Anthony, NM (Moderate) ^B	0.003
Clark Co [Las Vegas], NV (Serious)	1.200
Coachella Valley, CA (Serious)	0.239
El Paso Co, TX (Moderate) ^A	0.611
Hayden/Miami, AZ (Moderate)	0.004
Imperial Valley, CA (Moderate)	0.122
Los Angeles South Coast Air Basin, CA (Serious)	14.352
Nogales, AZ (Moderate)	0.025
Owens Valley, CA (Serious)	0.018
Phoenix, AZ (Serious)	2.977
San Joaquin Valley, CA (Serious)	3.214
Searles Valley, CA (Moderate)	0.029
Wallula, WA (Moderate) ^B	0.052
Washoe Co [Reno], NV (Moderate)	0.320
Total Areas: 14	23.167

^A EPA has determined that continuing PM₁₀ nonattainment in El Paso, TX is attributable to such transport under section 179(B).

^B The violation in this area has been determined to be attributable to natural events under section 188(f) of the Act.

In addition to the 14 PM₁₀ nonattainment areas that are currently violating the PM₁₀ NAAQS listed in Table II.A-13, there are 25 unclassifiable areas that have recently recorded ambient concentrations of PM₁₀ above the PM₁₀ NAAQS. EPA adopted a policy in 1996 that allows areas with PM₁₀ exceedances that are attributable to natural events to retain their designation as unclassifiable if the State is taking all reasonable measures to safeguard public health regardless of the sources of PM₁₀ emissions. Areas that remain unclassifiable areas are not required under the Clean Air Act to submit attainment plans, but we work with each of these areas to understand the nature of the PM₁₀ problem and to determine what best can be done to reduce it. With respect to the monitored violations reported in 1997-99 in the 25 areas designated as unclassifiable, we have not yet excluded the possibility that factors such as a one-time monitoring upset or natural events, which ordinarily would not result in an area being designated as nonattainment for PM₁₀, may be responsible for the problem. Emission reductions

from today's action will assist these currently unclassifiable areas to achieve ambient PM_{10} concentrations below the current PM_{10} NAAQS.

ii. *Risk of Future Exceedances of the PM_{10} Standard*

The new standards for heavy-duty vehicles will benefit public health and welfare through reductions in direct diesel particles and NO_x , VOCs, and SO_x which contribute to secondary formation of particulate matter. Because ambient particle concentrations causing violations of the PM_{10} standard are well established to endanger public health and welfare, this information supports the new standards for heavy-duty vehicles. The reductions from today's rule will assist states as they work with the Agency through implementation of local controls including development and adoption of additional controls as needed to move their areas into attainment by the applicable deadline, and maintain the standards thereafter.

The Agency's PM inventory analysis performed for this rulemaking predicts that without additional reductions 10 areas face a significant risk of failing to meet or to maintain the PM_{10} NAAQS even with federal, State and local controls currently in place. EPA has evaluated projected emissions for this analysis rather than future air quality because REMSAD, the model EPA has used for analyses related to this rule, was designed principally to estimate long-term average concentrations of fine particulate matter and its ability to predict short-term PM_{10} concentrations has not been satisfactorily demonstrated. In contrast with ozone, which is the product of complex photochemical reactions and therefore difficult to directly relate to precursor emissions, ambient PM_{10} concentrations are more heavily influenced by direct emissions of particulate matter and can therefore be correlated more meaningfully with emissions inventories. In the west, where most of the PM_{10} nonattainment areas are located, coarse PM is comprised of 70 percent particles composed of minerals, with only small fractions attributable to gaseous pollutants such as SO_x , NO_x and ammonia.[†]

Table II.A-14 presents information about these ten areas and subdivides them into two groups. The first group of six areas are designated PM_{10} nonattainment areas which had recent monitored violations of the PM_{10} NAAQS in 1997-1999 and increasing inventories of PM_{10} from 1996 to 2030. These areas have a population of 19 million. Included in the group are the nonattainment areas that are part of the Los Angeles, Phoenix and Las Vegas (Clark County) metropolitan areas, where traffic from heavy-duty vehicles is substantial. These six areas will benefit from the reductions in emissions that will occur from the new standards for heavy-duty vehicles, as will other areas impacted by heavy-duty vehicle emissions.

[†] *Air Quality Criteria for Particulate Matter*, External Review Draft, EPA 600/P-99/002a, Volume 1, October 1999, at 4.43.

The second group of four counties listed in Table II.A-14 with a total of nine million people in 1999 also had predicted exceedances of the PM₁₀ standard. These four areas registered, in either 1997 or 1998, single-year annual average monitored PM₁₀ levels of at least 90 percent of the PM₁₀ NAAQS, these areas did not exceed the formal definition of the PM₁₀ NAAQS over the three-year period ending in 1999. For each of these four areas (ie., Cuyahoga, Harris, New York, and San Diego), inventories of total PM₁₀ are predicted to increase between 1996, when these areas recorded values within 10 percent of the PM₁₀ standard, and 2030 when this rule will take full effect. For some of these areas, total PM₁₀ inventories are predicted to decline or stay relatively constant from 1996 to 2007, and then increase after 2007. Based on these inventory projections, the small margin of attainment which the four areas currently enjoy will likely erode between 1996 and 2030, and for some areas before 2007, if additional actions to reduce the growth of future emissions are not taken. We therefore consider these four areas to each individually have a significant risk of exceeding the PM₁₀ standard between 2007 and 2030 without further emission reductions. The emission reductions from the new standards for heavy-duty vehicles will help these areas attain and maintain the PM₁₀ NAAQS in conjunction with other processes that are currently moving these areas towards attainment.

Table II.A-14. Areas with Significant Risk of Exceeding the PM₁₀ NAAQS without Further Emission Reductions between 2007 and 2030

Area	Percent Increases in PM ₁₀ Emissions (1996-2030)	1999 Population (projected) (millions)
Areas Currently Exceeding the PM₁₀ standard		
Clark Co., NV (Las Vegas)	41%	1.217
El Paso, TX *	14%	0.611
Hayden/Miami, AZ	4%	0.004
Los Angeles South Coast Air Basin, CA	14%	14.352
Nogales, AZ	3%	0.025
Phoenix, AZ	24%	3.012
<i>Subtotal for 6 Areas</i>		<i>19.22</i>
Areas within 10% of Exceeding the PM₁₀ Standard		
Cuyahoga Co., OH (Cleveland)	28%	1.37
Harris, Co., TX (Houston)	37%	3.26
New York Co., NY	14%	1.55
San Diego Co., CA	13%	2.83
<i>Subtotal for 4 Areas</i>		<i>9.01</i>
10 Areas		28.23 million

* EPA has determined that PM₁₀ nonattainment in this area is attributable to international transport. While reductions in heavy-duty vehicle emissions cannot be expected to result in attainment, they will help reduce the degree of PM₁₀ nonattainment.

EPA recognizes that the SIP process is ongoing and that many of the 14 current nonattainment areas in Table II.A-13 are in the process of, or will be adopting and implementing additional control measures to achieve the PM₁₀ NAAQS in accordance with their attainment dates under the Clean Air Act. EPA believes, however, that as in the case of ozone, there are uncertainties inherent in any demonstration of attainment that is premised on forecasts of emission levels in future years. Even if these areas adopt and submit SIPs that EPA is able to approve as demonstrating attainment of the PM₁₀ standard, and attain the standard by the appropriate attainment dates, the inventory analysis conducted for this rule and the history of PM₁₀ levels in these areas indicates that there is still a significant risk that these areas will need the reductions from the heavy-duty vehicle standards adopted today to maintain the PM₁₀ standards in the long term (ie, between 2007 and 2030). In addition, this list does not fully consider the possibility that there are other areas which are now meeting the PM₁₀ NAAQS that have at least a significant probability of requiring further reductions to continue to maintain it.

iii. Conclusion

In sum, the Agency believes that ten areas listed in Table II.A-14 have a significant risk of experiencing particulate matter levels that violate the PM₁₀ standard from 2007 to 2030. In addition, this list does not fully consider the possibility that there are other areas which are now meeting the PM₁₀ NAAQS that have at least a significant probability of requiring further reductions to continue to maintain it.

b. Public Health and Welfare Concerns from Exposure to Fine PM*i. Health Effects Studies*

There are many studies supporting the Agency's belief that ambient PM causes health and welfare effects even in areas where PM₁₀ concentrations are below the level of PM₁₀ NAAQS. This science points to fine PM in particular as being more strongly associated with serious health effects, such as premature mortality, than coarse fraction PM. The health and welfare studies support a conclusion that fine PM patterns, that can reasonably be anticipated to occur in the future, are a serious public health and welfare concern warranting a requirement to reduce emissions from heavy-duty vehicles, even where they may not constitute violation of the PM₁₀ NAAQS.

The strongest evidence for ambient PM exposure health risks is derived from epidemiologic studies. The following brief summary focuses on studies completed in the last 10 years on the health and welfare effects of PM. A detailed summary and discussion of the large body of PM health effects research may be found in Chapters 10 to 13 of the 1996 Air Quality Criteria for Particulate Matter (known as the Criteria Document or CD).

Many epidemiologic studies have shown statistically significant associations of ambient PM levels with a variety of human health endpoints in sensitive populations, including mortality, hospital admissions and emergency room visits, respiratory illness and symptoms, and physiologic changes in mechanical pulmonary function. The epidemiologic science points to fine PM as being more strongly associated with some health effects, such as premature mortality, than coarse fraction PM, which is associated with other health effects.

Associations of both short-term and long-term PM exposure with most of these endpoints have been consistently observed. Peer-reviewed studies in a variety of locations implicate PM exposure in increased mortality at levels well below the current 24-hour PM₁₀ NAAQS of 150 $\mu\text{g}/\text{m}^3$ and annual PM₁₀ NAAQS of 50 $\mu\text{g}/\text{m}^3$. This section will briefly highlight the short-term exposure studies first and then some of the longer-term exposure studies.

The general internal consistency of the epidemiologic data base and available findings have led to increasing public health concern, due to the severity of several studied endpoints and the frequent demonstration of associations of health and physiologic effects with ambient PM levels at or below the current PM₁₀ NAAQS. Time-series analyses strongly suggest a positive effect on daily mortality across the entire range of ambient PM levels. Relative risk (RR) estimates for daily mortality in relation to daily ambient PM concentration are consistently positive, and statistically significant (at $P \leq 0.05$), across a variety of statistical modeling approaches and methods of adjustment for effects of relevant covariates such as season, weather, and co-pollutants. Questions remain about the influence of other factors and other issues, and are described in detail in the Criteria Document. However, even considering the uncertainties, the Agency believes that the weight of epidemiologic evidence suggests that ambient PM exposure has affected the public health of U.S. populations.

Within the body of evidence, there is considerable agreement among different studies that the elderly are particularly susceptible to effects from both short-term and long-term exposures to PM, especially if they have underlying respiratory or cardiac disease. These effects include increases in mortality and increases in hospital admissions. Children, especially those with respiratory diseases, may also be susceptible to pulmonary function decrements associated with exposure to PM or acid aerosols. Respiratory symptoms and reduced activity days have also been associated with PM exposures in children.

Numerous time-series analyses published in the late 1980s and early 1990s demonstrate significant positive associations between daily mortality or morbidity and 24-hour concentrations of ambient particles indexed by various measures (black smoke, TSP, PM₁₀, PM_{2.5}, etc.) in numerous U.S. metropolitan areas and in other countries (e.g., Athens, São Paulo, Santiago).^s These studies collectively suggest that PM alone or in combination with other commonly occurring air pollutants (e.g., SO₂) is associated with daily mortality and morbidity, the effect of PM appearing to be most consistent. In both the historic and recent studies, the association of PM exposure with mortality has been strongest in the elderly and for respiratory and cardiovascular causes of death.

Table II.A-15 summarizes effect estimates (relative risk information) derived from epidemiologic studies demonstrating health effects associations with ambient 24-hour PM₁₀ concentrations in U.S. and Canadian cities. The evidence summarized in Table II.A-17 leaves little doubt that PM concentrations typical of contemporary U.S. urban air sheds are correlated with detectable increases in risk of human mortality and morbidity. Evidence from studies that looked at PM indicators other than PM₁₀, summarized in Table II.A-16, also suggests that fine

^s In the tables summarizing the studies, relative risks with lower confidence intervals greater than 1.0 are statistically significant at the 95 percent confidence level. In Table II A-17, for example, the first entry showing Portage, WI, with a confidence interval of 0.98 - 1.09 is not statistically significant.

particles may be important contributors to the observed PM-health effects associations given the increased risks (of mortality, hospitalization, respiratory symptoms, etc.) associated with several different fine particle indicators (e.g., $PM_{2.5}$, SO_4^- , H^+). In particular, more recent reanalyses of the Harvard Six-City Study by Schwartz et al. (1996a) examined the effects on daily mortality of 24-hour concentrations of fine particles ($PM_{2.5}$), inhalable particles ($PM_{15/10}$), or coarse fraction particles ($PM_{15/10}$ minus $PM_{2.5}$) as exposure indices. Overall, these analyses suggest that, in general, the association between excess mortality and thoracic particles appears to be stronger for the fine than the coarse fraction.

In addition to short-term exposure effects, mortality and morbidity effects associated with long-term exposure to PM air pollution have been assessed in cross-sectional studies and more recently, in prospective cohort studies. A number of older cross-sectional studies provided indications of increased mortality associated with chronic exposures to ambient PM (indexed mainly by TSP or sulfate measurements); however, unresolved questions regarding adequacy of statistical adjustments for other potentially important covariates tended to limit the degree of confidence that could be placed on such studies.

Table II.A-17 summarizes some more recent studies using improved methods to examine relationships between chronic PM exposures indexed by different particle size indicators (PM_{15} , $PM_{2.5}$, PM_{15} to $PM_{2.5}$). These studies observed associations between increased risk of mortality/morbidity and chronic (annual average) exposures to PM_{10} or fine particle indicators in contemporary North American urban air sheds.

Since the completion of the 1996 PM Criteria Document (CD), many new epidemiological studies have been published. The PM Criteria Document for the current PM NAAQS review is now being prepared, and in the CD these many new studies will be reviewed, summarized, and integrated with what was learned in previous reviews. EPA will await the completion of the current PM CD before drawing conclusions regarding the findings of this new body of literature regarding the PM NAAQS.

Separate from the NAAQS review, however, new peer-reviewed studies may be considered for use in Regulatory Impact Analyses or other such analyses. EPA believes it appropriate to use the more recent scientific findings for these purposes, especially where the new information adds value to the analyses. Some of these new studies are described below, and the findings of these studies will be incorporated in the larger review of the literature contained in the next PM CD.

Two new Health Effects Institute (HEI) funded studies have received substantial attention from both scientists and the public: a multi-city analysis of mortality and morbidity associations with PM_{10} and other air pollutants (Samet et al., 2000) and the reanalysis of two previous studies of mortality associations with long-term exposure to PM (Krewski et al., 2000).

The multi-city study, National Morbidity, Mortality and Air Pollution Study (NMMAPS), evaluated associations between air pollutants and mortality in 90 U.S. cities, and also evaluated associations between air pollutants and hospital admissions among the elderly in 14 U.S. cities. The authors report: “Together, the 2 sets of analyses - that of mortality in 90 cities and hospitalization in 14 cities - provide new and strong evidence linking particulate air pollution to adverse health effects.” (Samet et al., 2000, p. 42)

In the Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality, data were obtained from the original investigators for two previous studies (Dockery et al., 1993; Pope et al., 1995). The extensive analyses included replication and validation of the previous findings, as well as sensitivity analyses using alternative analytic techniques, including different methods of covariate adjustment, exposure characterization, and exposure-response modeling. The authors concluded: “The risk estimates reported by the Original Investigators were remarkably robust to alternative specifications of the underlying risk models, thereby strengthening confidence in the original findings.” (Krewski et al., 2000, p. 234)

Some of these new epidemiology studies have presented interesting new findings related to mobile source emissions. For example, Laden et al. (2000) used factor analysis with indicators of particulate matter from several sources, and reported that among these sources, particulate matter from mobile sources had the largest association with mortality in six U.S. cities. Mar et al. (2000) conducted a similar analysis using data from Phoenix, Arizona, and report that mortality from cardiovascular diseases was associated with motor vehicle exhaust-related pollutants. An additional new analysis uses the results of a number of new epidemiological studies to assess the public health impact of outdoor and traffic-related pollution for three European countries. The authors report findings of “considerable” public health impacts for both mortality and morbidity (e.g., bronchitis, exacerbation of existing asthma) effects (Kunzli et al., 2000). These new studies suggest that particles from mobile source emissions play a role in ambient PM-related health effects.

In conclusion, the weight of epidemiologic evidence suggests that PM exposures are correlated with a variety of serious health effects at levels well below the current 24-hour PM_{10} NAAQS of $150 \mu\text{g}/\text{m}^3$ and annual PM_{10} NAAQS of $50 \mu\text{g}/\text{m}^3$. Similarly, although relatively few cohort studies of long-term PM exposure and mortality are available, they are consistent in direction and magnitude of excess risk with a larger body of cross-sectional annual mortality studies, and most show positive associations of PM exposure with mortality.

Table II.A-15. Effect Estimates Per 50 $\mu\text{g}/\text{m}^3$ Increase in 24-hour PM_{10} Concentrations From U.S. And Canadian Studies

<i>Study Location</i>	<i>RR (\pm CI*) Only PM in Model</i>	<i>Reported PM₁₀ Levels Mean (Min/Max)[†]</i>
Increased Total Short-term Exposure Mortality		
Six Cities^A		
Portage, WI	1.04 (0.98, 1.09)	18 (\pm 11.7)
Boston, MA	1.06 (1.04, 1.09)	24 (\pm 12.8)
Topeka, KS	0.98 (0.90, 1.05)	27 (\pm 16.1)
St. Louis, MO	1.03 (1.00, 1.05)	31 (\pm 16.2)
Kingston/Knoxville, TN	1.05 (1.00, 1.09)	32 (\pm 14.5)
Steubenville, OH	1.05 (1.00, 1.08)	46 (\pm 32.3)
St. Louis, MO ^C	1.08 (1.01, 1.12)	28 (1/97)
Kingston, TN ^C	1.09 (0.94, 1.25)	30 (4/67)
Chicago, IL ^H	1.04 (1.00, 1.08)	37 (4/365)
Chicago, IL ^G	1.03 (1.02, 1.04)	38 (NR/128)
Utah Valley, UT ^B	1.08 (1.05, 1.11)	47 (11/297)
Birmingham, AL ^D	1.05 (1.01, 1.10)	48 (21, 80)
Los Angeles, CA ^F	1.03 (1.00, 1.055)	58(15/177)
Increased Hospital Admissions (for Elderly > 65 yrs.)		
Respiratory Disease		
Toronto, CAN ^I	1.23 (1.02, 1.43) [‡]	30-39 [§]
Tacoma, WA ^J	1.10 (1.03, 1.17)	37 (14, 67)
New Haven, CT ^J	1.06 (1.00, 1.13)	41 (19, 67)
Cleveland, OH ^K	1.06 (1.00, 1.11)	43 (19, 72)
Spokane, WA ^L	1.08 (1.04, 1.14)	46 (16, 83)
Chronic Obstructive Pulmonary Disease		
Minneapolis, MN ^N	1.25 (1.10, 1.44)	36 (18, 58)
Birmingham, AL ^M	1.13 (1.04, 1.22)	45 (19, 77)
Spokane, WA ^L	1.17 (1.08, 1.27)	46 (16, 83)
Detroit, MI ^O	1.10 (1.02, 1.17)	48 (22, 82)

Table II.A-15 continues on next page.

Table II.A-15 (cont'd). Effect Estimates per 50 $\mu\text{g}/\text{m}^3$ Increase in 24-hour PM_{10} Concentrations from U.S. and Canadian Studies

<i>Study Location</i>	<i>RR (\pm CI*) Only PM in Model</i>	<i>RR (\pm CI*) Other Pollutants in Model</i>	<i>Reported PM₁₀ Levels Mean (Min/Max)[†]</i>
<u>Pneumonia</u>			
Minneapolis, MN ^N	1.08 (1.01, 1.15)	—	36 (18,58)
Birmingham, AL ^M	1.09 (1.03, 1.15)	—	45 (19, 77)
Spokane, WA ^L	1.06 (0.98, 1.13)	—	46 (16, 83)
Detroit, MI ^O	—	1.06 (1.02, 1.10)	48 (22, 82)
<u>Ischemic HD</u>			
Detroit, MI ^P	1.02 (1.01, 1.03)	1.02 (1.00, 1.03)	48 (22, 82)
<u>Increased Respiratory Symptoms</u>			
<u>Lower Respiratory</u>			
Six Cities ^Q	2.03 (1.36, 3.04)	Similar RR	30 (13,53)
Utah Valley, UT ^R	1.28 (1.06, 1.56) [‡]	—	46 (11/195)
	1.01 (0.81, 1.27) ^π		
Utah Valley, UT ^S	1.27 (1.08, 1.49)	—	76 (7/251)
<u>Cough</u>			
Denver, CO ^X	1.09 (0.57, 2.10)	—	22 (0.5/73)
Six Cities ^Q	1.51 (1.12, 2.05)	Similar RR	30 (13, 53)
Utah Valley, UT ^S	1.29 (1.12, 1.48)	—	76 (7/251)
<u>Decrease in Lung Function</u>			
Utah Valley, UT ^R	55 (24, 86) ^{**}	—	46 (11/195)
Utah Valley, UT ^S	30 (10, 50) ^{**}	—	76 (7/251)
Utah Valley, UT ^W	29 (7,51) ^{***}	—	55 (1,181)

* CI = Confidence Interval.

† Min/Max 24-h PM_{10} in parentheses unless noted otherwise as standard deviation (\pm S.D), 10 and 90 percentile (10, 90). NR = not reported.

‡ Children.

π Asthmatic children and adults.

§ Means of several cities.

‡ RR refers to total population, not just >65 years.

** PEFV decrease in ml/sec.

*** FEV₁ decrease.

Table II.A-15 References

^A Schwartz et al. (1996a).

^B Pope et al. (1992, 1994)/O₃.

^C Dockery et al. (1992)/O₃.

^D Schwartz (1993).

^F Kinney et al. (1995)/O₃, CO.

^G Ito and Thurston (1996)/O₃.

^H Styer et al. (1995).

^I Thurston et al. (1994)/O₃.

^J Schwartz (1995)/SO₂.

^K Schwartz et al. (1996b).

^L Schwartz (1996).

^M Schwartz (1994e).

^N Schwartz (1994f).

^O Schwartz (1994d).

^P Schwartz and Morris (1995)/O₃, CO, SO₂.

^Q Schwartz et al. (1994).

^R Pope et al. (1991).

^S Pope and Dockery (1992).

^T Schwartz (1994g).

^W Pope and Kanner (1993).

^X Ostro et al. (1991).

Table II.A-16. Effect Estimates per Variable Increments in 24-hour Concentrations of Fine Particle Indicators (PM_{2.5}, SO₄⁻, H⁺) From U.S. and Canadian Studies

<i>Short-term Exposure Mortality</i>	<i>Indicator</i>	<i>RR (± CI*) per 25 µg/m³ PM Increase</i>	<i>Reported PM Levels Mean (Min/Max)[†]</i>
Six City^A			
Portage, WI	PM _{2.5}	1.030 (0.993, 1.071)	11.2 (±7.8)
Topeka, KS	PM _{2.5}	1.020 (0.951, 1.092)	12.2 (±7.4)
Boston, MA	PM _{2.5}	1.056 (1.038, 1.0711)	15.7 (±9.2)
St. Louis, MO	PM _{2.5}	1.028 (1.010, 1.043)	18.7 (±10.5)
Kingston/Knoxville, TN	PM _{2.5}	1.035 (1.005, 1.066)	20.8 (±9.6)
Steubenville, OH	PM _{2.5}	1.025 (0.998, 1.053)	29.6 (±21.9)
Increased Hospitalization			
Ontario, CAN ^B	SO ₄ ⁻	1.03 (1.02, 1.04)	R = 3.1-8.2
Ontario, CAN ^C	SO ₄ ⁻	1.03 (1.02, 1.04)	R = 2.0-7.7
	O ₃	1.03 (1.02, 1.05)	
NYC/Buffalo, NY ^D	SO ₄ ⁻	1.05 (1.01, 1.10)	NR
Toronto ^D	H ⁺ (Nmol/m ³)	1.16 (1.03, 1.30) [‡]	28.8 (NR/391)
	SO ₄ ⁻	1.12 (1.00, 1.24)	7.6 (NR, 48.7)
	PM _{2.5}	1.15 (1.02, 1.78)	18.6 (NR, 66.0)
Increased Respiratory Symptoms			
Southern California ^F	SO ₄ ⁻	1.48 (1.14, 1.91)	R = 2-37
Six Cities ^G	PM _{2.5}	1.19 (1.01, 1.42)**	18.0 (7.2, 37)***
(Cough)	PM _{2.5} Sulfur	1.23 (0.95, 1.59)**	2.5 (3.1, 61)***
	H ⁺	1.06 (0.87, 1.29)**	18.1 (0.8, 5.9)***
Six Cities ^G	PM _{2.5}	1.44 (1.15-1.82)**	18.0 (7.2, 37)***
(Lower Resp. Symp.)	PM _{2.5} Sulfur	1.82 (1.28-2.59)**	2.5 (0.8, 5.9)***
	H ⁺	1.05 (0.25-1.30)**	18.1 (3.1, 61)***
Decreased Lung Function			
Uniontown, PA ^E	PM _{2.5}	PEFR 23.1 (-0.3, 36.9) (per 25 µg/m ³)	25/88 (NR/88)

* CI = Confidence Interval.

† Min/Max 24-h PM indicator level shown in parentheses unless otherwise noted as (± S.D.), 10 and 90 percentile (10,90) or R = range of values from min-max, no mean value reported. NR = not reported.

‡ Change per 100 nmoles/m³.

** Change per 20 µg/m³ for PM_{2.5}; per 5 µg/m³ for PM_{2.5} sulfur; per 25 nmoles/m³ for H⁺.

*** 50th percentile value (10,90 percentile).

Table II.A-16 References

^A Schwartz et al. (1996a).

^B Burnett et al. (1994).

^C Burnett et al. (1995) O₃.

^D Thurston et al. (1992, 1994)

^E Neas et al. (1995).

^F Ostro et al. (1993).

^G Schwartz et al. (1994).

Table II.A-17. Effect Estimates per Increments* in Annual Mean Levels of Fine Particle Indicators from U.S. and Canadian Studies

<i>Type of Health Effect & Location</i>	<i>Indicator</i>	<i>Change in Health Indicator per Increment in PM*</i>	<i>Range of City PM Levels Means ($\mu\text{g}/\text{m}^3$)</i>
Increased total chronic mortality in adults		Relative Risk (95% CI)	
Six City ^B	PM _{15/10}	1.42 (1.16-2.01)	18-47
	PM _{2,5}	1.31 (1.11-1.68)	11-30
	SO ₄ ⁻	1.46 (1.16-2.16)	5-13
ACS Study ^C (151 U.S. SMSA)	PM _{2,5}	1.17 (1.09-1.26)	9-34
	SO ₄ ⁻	1.10 (1.06-1.16)	4-24
Increased bronchitis in children		Odds Ratio (95% CI)	
Six City ^D	PM _{15/10}	3.26 (1.13, 10.28)	20-59
Six City ^E	TSP	2.80 (1.17, 7.03)	39-114
24 City ^F	H ⁺	2.65 (1.22, 5.74)	6.2-41.0
24 City ^F	SO ₄ ⁻	3.02 (1.28, 7.03)	18.1-67.3
24 City ^F	PM _{2,1}	1.97 (0.85, 4.51)	9.1-17.3
24 City ^F	PM ₁₀	3.29 (0.81, 13.62)	22.0-28.6
Southern California ^G	SO ₄ ⁻	1.39 (0.99, 1.92)	—
Decreased lung function in children			
Six City ^D	PM _{15/10}	No significant changes	20-59
Six City ^E	TSP	No significant changes	39-114
24 City ^{I,J}	H ⁺ (52 nmoles/m ³)	-3.45% (-4.87, -2.01) FVC	—
24 City ^I	PM _{2,1} (15 $\mu\text{g}/\text{m}^3$)	-3.21% (-4.98, -1.41) FVC	—
24 City ^I	SO ₄ ⁻ (7 $\mu\text{g}/\text{m}^3$)	-3.06% (-4.50, -1.60) FVC	—
24 City ^I	PM ₁₀ (17 $\mu\text{g}/\text{m}^3$)	-2.42% (-4.30, -0.51) FVC	—

* Estimates calculated annual-average PM increments assume: a 100 $\mu\text{g}/\text{m}^3$ increase for TSP; a 50 $\mu\text{g}/\text{m}^3$ increase for PM₁₀ and PM₁₅; a 25 $\mu\text{g}/\text{m}^3$ increase for PM_{2,5}; and a 15 $\mu\text{g}/\text{m}^3$ increase for SO₄⁻, except where noted otherwise; a 100 nmole/m³ increase for H⁺.

Table II.A-17 References

^B Dockery et al. (1993)

^E Ware et al. (1986)

^I Raizenne et al. (1996)

^C Pope et al. (1995)

^F Dockery et al. (1996)

^J Pollutant data same as for

^D Dockery et al. (1989)

^G Abbey et al. (1995a,b,c)

Dockery et al. (1996)

Statistically significant increased mortality from daily exposures to fine PM was observed in cities with longer-term average fine PM concentrations in the range of 16 to 21 ug/m³. It is reasonable to anticipate that populations exposed to similar or higher levels, now and in the 2007 and later time frame, will also experience cases of premature mortality attributable to short term exposures to fine PM. In addition to mortality, statistically significant relationships between daily fine PM levels (or close indicators of fine PM) and increased respiratory symptoms, decreased lung functions, and increased hospitalizations, have also been observed in U.S. cities.

ii. Current and Future Exposures

At the beginning of 1999, State environmental agencies began operating a broad network of monitoring stations for the measurement of fine particulate matter (measured as particulate matter having an aerometric diameter less than or equal to 2.5 micrometers, or PM_{2.5}), using the Federal Reference Method for PM_{2.5} mass established when the PM_{2.5} national ambient air quality standard was promulgated (62 FR 38763, July 18, 1997). The data that have been submitted to EPA from this network are available in summary form via the internet on EPA's website (http://www.epa.gov/aqspubl1/annual_summary.html). Copies of raw data may be obtained by contacting the Information Management Group, Information Transfer and Program Integration Division within the Office of Air Quality Planning and Standards. Monitors are generally located within metropolitan statistical areas, although some monitors intended to measure upwind PM_{2.5} concentrations are located outside of metropolitan areas. Monitors in this network report a 24-hour average PM_{2.5} concentration for each day of successful monitoring.

At present, virtually all States have completed the quality assurance review and certification process. Data which have been certified as valid are considered to be reliable, although for the purposes of characterizing air quality in areas to which people may be exposed, there must also be a sufficient number of valid samples during the period in question. For the purposes of this analysis, we have only included data certified by the States as valid, and have included only data from sites recording eleven or more valid samples in each calendar quarter. These data are not sufficient for determining whether given areas should be designated under the Clean Air Act as attainment or nonattainment with the PM_{2.5} NAAQS. Under EPA regulations, this would require consideration of 3 years of valid data. However, these data provide a sufficient basis to estimate the number of people who lived in monitored counties in 1999 in which annual average concentrations of PM_{2.5} equaled or exceeded certain specified values.

In this analysis, we focus on the long-term average concentrations of PM_{2.5}. Accordingly, we analyze the 1999 PM_{2.5} monitoring data, as available, quality assured, and certified by the states, to estimate the long-term average concentration at each monitor for the final rule. These data will not be sufficient for predicting attainment or nonattainment with the PM_{2.5} NAAQS, which requires three years of data. However, for the purpose of this analysis, the currently available monitor data will suffice.

Current 1999 PM_{2.5} monitored values, which cover about a third of the nation's counties, indicate that at least 40 million people live in areas where long term ambient fine particulate matter levels are at or above 16 µg/m³ (37 percent of the population in the areas with monitors), which is the low end of the range of long term average PM_{2.5} concentrations in cities where statistically significant associations were found with serious health effects, including premature mortality (EPA, 1996).[†]

Our REMSAD modeled predictions allow us to also estimate the affected population for the counties which do not currently have PM_{2.5} monitors. According to our national modeled predictions, there were a total of 76 million people (1996 populations) living in areas with modeled annual average PM_{2.5} concentrations at or above 16 µg/m³ (29 percent of the population).[‡]

The REMSAD model also allows us to estimate future PM_{2.5} levels. However, the most appropriate method of making these projections relies on the model to predict changes between current and future states. Thus, we have estimated future conditions only for the areas with current PM_{2.5} monitored data (which, as just noted, covers about a third of the nation's counties). For these counties, REMSAD predicts the current level of 37 percent of the population living in areas where fine PM levels are at or above 16 µg/m³ to increase to 59 percent in 2030.

It is reasonable to anticipate that sensitive populations exposed to similar or higher levels, now and in the 2007 and later time frame, will also be at increased risk of premature mortality associated with exposures to fine PM. In addition, statistically significant relationships have also been observed in U.S. cities between PM levels and increased respiratory symptoms and decreased lung functions in children.

Since EPA's examination in the mid-1990s of the epidemiological and toxicological evidence of the health effects of PM, many new studies have been published that reevaluate or extend the initial research. The Agency is currently reviewing these new studies to stay abreast of the literature and adjust as necessary its assessment of PM's health effects. It is worth noting that within this new body of scientific literature, there are two new studies funded by the Health Effects Institute, a EPA-industry jointly funded group, that have generally confirmed the mid-1990s findings of the Agency about the association of fine particles and premature mortality and various other respiratory and cardiovascular effects. HEI's *National Morbidity, Mortality and Air Pollution Study* (NMMAPS), evaluated associations between air pollutants and mortality in 90 U.S. cities, and also evaluated associations between air pollutants and hospital admissions

[†] EPA (1996) Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information OAQPS Staff Paper. EPA-452/R-96-013.

[‡] REMSAD modeling for PM_{2.5} annual average concentrations. Total 1996 population in all REMSAD grid cells is 263 million

among the elderly in 14 U.S. cities.^v In HEI's *Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality*, data were obtained from the original investigators for two previous studies.^{w x} The extensive analyses included replication and validation of the previous findings, as well as sensitivity analyses using alternative analytic techniques, including different methods of covariate adjustment, exposure characterization, and exposure-response modeling.^y

In conclusion, we believe that in the period 2007 to 2030, when the standards adopted in today's action will help reduce ambient PM_{2.5} concentrations, a significant portion of the US population may be exposed to ambient PM_{2.5} concentrations that studies have found may cause adverse health effects.

4. Diesel Exhaust

The following section presents information about the health hazard and potential risk to public health and welfare posed by exposure to diesel exhaust. The finding of a health hazard addresses the question of whether exposure to an agent is likely to cause an adverse human effect, whereas a discussion of risk is an attempt to provide information on the possible exposure-related impact of the hazard for an exposed population. In this section, we describe in some detail the cancer, chronic noncancer, and acute health effects associated with exposure to diesel exhaust and provide the Agency's current position on the potential for environmental concern. Ambient concentrations and exposure to diesel particulate matter are also described to put the hazard conclusions in perspective.

a. Cancer and Noncancer Effects of Diesel Exhaust

The EPA has concluded that diesel exhaust is likely to be carcinogenic to humans by inhalation at occupational and environmental levels of exposure.¹⁷ Available evidence shows that exposure to diesel exhaust may also cause adverse noncancer health effects with episodic,

^v Samet JM, Zeger SL, Dominici F, Curriero F, Coursac I, Dockery DW, Schwartz J, Zanobetti A. 2000. The National Morbidity, Mortality and Air Pollution Study: Part II: Morbidity, Mortality and Air Pollution in the United States. Research Report No. 94, Part II. Health Effects Institute, Cambridge MA, June 2000.

^w Dockery, D.W., Pope, C.A., III, Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E. (1993) An association between air pollution and mortality in six U.S. cities. *N. Engl. J. Med.* 329:1753-1759.

^x Pope, C. A., III, Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., Speizer, F. E., Heath, C. W., Jr. (1995) Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. *Am. J. Respir. Crit. Care Med.* 151: 669-674.

^y Krewski D, Burnett RT, Goldbert MS, Hoover K, Siemiatycki J, Jerrett M, Abrahamowicz M, White WH.(2000) Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality. Special Report to the Health Effects Institute, Cambridge MA, July 2000

acute exposures, as well as noncancer and cancer effects to the respiratory system at longer term, chronic exposures. The draft *Health Assessment Document for Diesel Exhaust* (draft Assessment), was reviewed in public session by the Clean Air Scientific Advisory Committee (CASAC) on October 12-13, 2000.¹⁸ CASAC found that the Agency's conclusion that diesel exhaust is likely to be carcinogenic to humans is scientifically sound. CASAC concurred with the draft Assessment's findings with the proviso that EPA provide modifications and clarifications on certain topics. The Agency expects to produce the finalized Assessment in early 2001. Information presented here is consistent with that to be provided in the final Assessment.

In the draft Assessment, the Agency presents evidence to support its determination that exposure to diesel exhaust is likely to pose a carcinogenic hazard to humans. The most compelling information to suggest a carcinogenic hazard is the consistent association that has been observed between increased lung cancer and diesel exhaust exposure in certain occupationally exposed workers working in the presence of diesel engines. In its review of the published literature, EPA found that about 30 individual epidemiologic studies show increased lung cancer risk associated with diesel emissions. In the draft Assessment EPA evaluated 22 studies that were most relevant for risk assessment, 16 of which reported significant increased lung cancer risks, ranging from 20 to 167 percent, associated with diesel exhaust exposure. These studies are of varying quality in terms of design and controlling for factors that might confound a lung cancer response.

Published analytical results of pooling the positive study results show that on average the lung cancer risks were increased by 33 to 47 percent within a range of 20-89 percent across the studies. Individual epidemiological studies numbering about 30 show increased lung cancer risks of 20 to 89 percent within the study populations depending on the study. The magnitude of the pooled risk increases is not precise owing to uncertainties in the individual studies, the most important of which is a continuing concern about whether smoking effects have been accounted for adequately and in some cases whether other PM exposures were also present. While not all studies have demonstrated an increased risk (six of 34 epidemiological studies summarized by the Health Effects Institute¹⁹ reported relative risks less than 1.0), the fact that an increased risk has been consistently noted in the majority of epidemiological studies strongly supports the determination that exposure to diesel exhaust is likely to pose a carcinogenic hazard to humans.

Additional evidence supporting the identification of a cancer hazard for diesel exhaust includes the observation tumors in animals following applications of various fractions of the diesel exhaust mixture to skin, and implantation of diesel particles in respiratory tissue. Recognizing that diesel exhaust is a complex mixture of carbon particles and associated organics and other inorganics, it is unclear what fraction or combination of fractions is responsible for the carcinogenicity and other respiratory effects. It has been shown, however, that the carbon particles as well as the organics have the potential to be active toxicological agents, either because of the potential to be irritants which cause inflammation, or because of a capacity to produce mutagenic and/or carcinogenic activity. In the case of the organics (which exist both in particle and gaseous states in diesel exhaust) some have potent mutagenic and carcinogenic

properties. In addition, some evidence for the bioavailability of these particle adsorbed compounds has been demonstrated which supports a hypothesis that the adsorbed organics are bioavailable to the lung as well as being transported to sites distant from the lung.

While much of the available evidence for a cancer hazard in humans comes from occupational exposures which generally have higher exposures than in the ambient environment, there is a basis to infer that the lung cancer hazard extends to ambient environmental exposures. The basis for the ambient environmental cancer hazard recommendation is due, in part, to the observation that some ambient environmental concentrations and thus exposures are close to or overlap low-end occupational exposure estimates as discussed below. This potential overlap in exposures suggests that little extrapolation is necessary or, conversely, that there is no margin or only a small margin of safety for some in the general population when compared to occupational exposures where increased cancer risk is observed. Key to the extrapolation is the assumption that across any population showing a risk, that risk would be proportional to total lifetime exposure. The proportional assumption is always made by EPA unless there is evidence to the contrary, and in the case of diesel exhaust, the extrapolation of occupational risk to environmental exposure levels is more confidently judged to be appropriate due to the potential for small exposure differences.

Additional evidence for treating diesel exhaust as a carcinogen at ambient levels of exposure is provided by the observation of the presence of small quantities of many mutagenic and some carcinogenic compounds in the diesel exhaust. A carcinogenic response believed to be caused by such agents is assumed not to have a threshold unless there is direct evidence to the contrary. This is an EPA risk assessment policy choice in the absence of clear contrary evidence. In addition, there is evidence that at least some of the organic compounds associated with diesel particulate matter are extracted by lung fluids (i.e., are bioavailable) and, therefore, are available in some quantity to the lungs as well as entering the bloodstream and being transported to other sites in the body.

In the late 1980s, the International Agency for Research on Cancer (IARC) determined that diesel exhaust is “probably carcinogenic to humans” and the National Institute for Occupational Safety and Health classified diesel exhaust a “potential occupational carcinogen.”²⁰ ²¹ Based on IARC findings, the State of California identified diesel exhaust in 1990 as a chemical known to the State to cause cancer. In 1996, the International Programme on Chemical Safety of the World Health Organization listed diesel exhaust as a “probable” human carcinogen.²² In 1998, the California Office of Environmental Health Hazard Assessment (OEHHA, California EPA) identified diesel PM as a toxic air contaminant due to the noncancer and cancer hazard and because of the potential magnitude of the cancer risk.²³ Most recently, the U.S. Department of Health and Human Services National Toxicology Program designated diesel exhaust particles as “reasonably anticipated to be a human carcinogen” in its Ninth Report on Carcinogens.²⁴ The concern for a carcinogenicity hazard resulting from diesel exhaust exposures is longstanding and widespread.

The adverse noncancer effects of diesel exhaust are also of concern to the Agency. Acute (usually episodic, short duration, high concentration) exposures to diesel exhaust have been associated with a variety of inflammation-related symptoms such as headache, eye discomfort, asthma-like reactions, nausea and exacerbation or initiation of allergic hypersensitivity. No specific recommendations are made by EPA at this juncture about safe or unsafe exposures to protect from acute effects, since the onset of acute effects is so variable in the population and the available acute health effects data lacks adequate detail regarding dose-response relationships. The potential allergenic effects area of diesel exhaust are of growing interest in the health research community and as additional information emerges, additional review may be warranted.

Chronic (frequent or continuous, long duration, lower concentrations) diesel exhaust exposure, at sufficient inhalation levels, is judged to constitute a chronic noncancer respiratory hazard for humans. For chronic diesel exhaust exposure, EPA is completing the development of an inhalation reference concentration (RfC) for diesel exhaust exposure. The RfC is an estimate of the continuous human inhalation exposure (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious noncancer effects during a lifetime. While the limited amount of human data are suggestive of respiratory distress, animal test data are quite definitive in providing a basis to anticipate a hazard to the human lung based on the irritant and inflammatory reactions in the lung of test animals. Thus, EPA believes that chronic diesel exhaust exposure, at sufficient exposure levels, increases the hazard and risk of an adverse health effect. Based on CASAC advice regarding the use of the animal data to derive the RfC, the Agency will provide an RfC based on diesel exhaust effects in test animals of approximately 5 $\mu\text{g}/\text{m}^3$.

In addition, it is also instructive to recognize that diesel exhaust particulate matter is part of ambient fine PM. A qualitative comparison of adverse effects of exposure to ambient fine PM and diesel exhaust particulate matter shows that the respiratory system is adversely affected in both cases, though a wider spectrum of adverse effects has been identified for ambient fine PM. Relative to the diesel PM database, there is a wealth of human data for fine PM noncancer effects. Since diesel exhaust PM is a component of ambient fine PM, the fine PM health effects data base can be informative. The final Assessment will discuss the fine PM health effects data and its relation to evaluating health effects associated with diesel exhaust.

b. The Link Between Diesel Exhaust and Diesel Particulate Matter

Diesel exhaust includes components in the gas and particle phases. Gaseous components of diesel exhaust include nitrogen compounds, sulfur compounds, organic compounds, carbon monoxide, carbon dioxide, water vapor, and excess air (nitrogen and oxygen). Among these gas-phase constituents, at least one of the organic compounds is a known human carcinogen (e.g., benzene) while possible or probable human carcinogens are present (e.g., formaldehyde, acetaldehyde, 1,3-butadiene), along with compounds for which the Agency has set inhalation reference concentrations as a guidance to protect the public from noncancer health effects (e.g., acetaldehyde, acrolein, naphthalene).

Diesel particulate matter is either directly emitted from diesel-powered engines (primary particulate matter) or is formed from the gaseous compounds emitted by a diesel engine (secondary particulate matter). After emission from the tail-pipe, diesel exhaust undergoes dilution, reaction and transport in the atmosphere. The primary emission is considered 'fresh', while 'aged' diesel exhaust is considered to have undergone chemical and physical transformation. In an urban or industrial environment, or downwind of an area with large emission sources, diesel exhaust may enter an atmosphere with high concentrations of compounds capable of transforming some diesel particulate matter organic constituents into compounds which exhibit greater toxicity than the primary emitted particle. The formation of nitroarenes is one example of atmospheric transformation of a diesel exhaust organic compound to a more toxicologically significant compound.²⁵ Some assessments report up to 16 organic compounds in primary and secondary diesel exhaust with known or suspected carcinogenic activity or other toxicologically significant effects.²⁶

Primary diesel particles mainly consist of carbonaceous material, with a small contribution from sulfuric acid and ash (trace metals). Many of these particles exist in the atmosphere as a carbon core with a coating of organic carbon compounds, or as sulfuric acid and ash, sulfuric acid aerosols, or sulfate particles associated with organic carbon.²⁷ While representing a very small portion (less than one percent) of the national emissions of metals, and representing a small portion of diesel particulate matter (one to five percent), we note that several trace metals that may have general toxicological significance depending on the specific species are also emitted by diesel engines in small amounts including chromium, manganese, mercury and nickel. In addition, small amounts of dioxins have been measured in diesel exhaust, some of which may partition into the particle phase.

Approximately 80-95 percent of diesel particle mass is in the size range from 0.05-1.0 micrometers with a mean particle diameter of about 0.2 micrometers. These fine particles have a very large surface area per gram of mass, which make them excellent carriers for adsorbed inorganic and organic compounds that can effectively reach the lowest airways of the lung. Approximately 50-90 percent of the number of particles in diesel exhaust are in the ultrafine size range from 0.005-0.05 micrometers, averaging about 0.02 micrometers. While accounting for the majority of the number of particles, ultrafine diesel particulate matter accounts for 1-20 percent of the mass of diesel particulate matter.

Diesel particulate matter is mainly attributable to the incomplete combustion of fuel hydrocarbons as well as engine oil and other fuel components such as sulfur. Diesel exhaust particles are part of ambient $PM_{2.5}$, since diesel engines are used to power numerous types of equipment in many places. Some geographic areas may have higher diesel particulate loading because of the number of engines that exhaust into the ambient air. While diesel particulate matter contributes to ambient levels of $PM_{2.5}$, the high content of elemental carbon with the adsorbed organic compounds and the high number of ultrafine particles (organic carbon and sulfate) in diesel exhaust distinguish it from other noncombustion sources of $PM_{2.5}$. In addition, diesel particulate matter from mobile source diesel engines is emitted into the breathing zone of

humans and thus has a greater potential for human exposure (per kg of emissions) compared to other combustion particles emitted out of stacks.

While some of the cancer risk may be associated with exposure to the gaseous components of diesel exhaust, studies suggest that the particulate component plays a substantial role in carcinogenicity and noncancer effects. Investigations show that diesel particles (the elemental carbon core plus the adsorbed organics) induce lung cancer at high doses, and that the particles, independent of the gaseous compounds, elicit an animal lung cancer response. The presence of non-diesel elemental carbon particles, as well as the organic-laden diesel particles, correlate with an adverse inflammatory effect in the respiratory system of animals. Additional evidence suggesting the importance of the role of particulate matter in diesel exhaust includes the observation that the extractible particle organics collectively produce cancer and mutagenic toxicity in experimental test systems. Many of the individual organic compounds are mutagenic or carcinogenic in their own right. EPA believes that exposure to whole diesel exhaust is best described, as many researchers have done over the years, by diesel exhaust concentrations expressed in units of mass concentration, i.e., micrograms/m³. This dosimeter does not directly quantify the gaseous component of diesel exhaust exposure.

Overall, information suggests that the diesel particle may be playing a key role(s) in contributing to the chronic noncancer and carcinogenicity hazards associated with exposure to diesel exhaust: both as a mechanism of delivery for many of the organics and trace metals into the respiratory system, and as a physical irritant in and of itself. Given the available information, it is a reasonable and prudent step to protect public health by proposing regulations on diesel exhaust. Today's action will reduce exposure to both the particulate phase and the gaseous component of diesel exhaust as a result of the particulate matter and NMHC standards adopted. The emission standards and fuel sulfur limit would not directly limit emissions of trace metals, but may indirectly do so by encouraging engine designs with better control of engine oil consumption.^z

c. Ambient Concentrations and Exposure to Diesel Exhaust

As stated previously, the current Agency position is that diesel exhaust is likely to be carcinogenic to humans and that this cancer hazard exists for occupational as well as ambient levels of exposure. To provide a context in which to assess the potential hazard from ambient levels of diesel exhaust, EPA uses the mass concentration of diesel particulate matter (as do many researchers) as the exposure metric for whole diesel exhaust. A summary of diesel particulate matter concentrations is found in Table II.A-21 and levels of ambient exposure and occupational exposure for some job categories are presented in Table II.A-22.

^z We are also proposing in today's action to prohibit the introduction of used motor oil into the fuel delivery system which would reduce the trace metal content of the fuel (See Section VIII).

i. Ambient Concentrations

Information about ambient concentrations of diesel particulate matter and the relative contribution of diesel engines to ambient particulate matter levels is available from source-receptor models, dispersion models, and elemental carbon measurements. The most commonly used receptor model for quantifying concentrations of diesel particulate matter at a receptor site is the chemical mass balance model (CMB). Input to the CMB model includes particulate matter measurements made at the receptor site as well as measurements made of each of the source types suspected to impact the site. Because of problems involving the elemental similarity between diesel and gasoline emission profiles and their co-emission in time and space, it is useful to carefully quantify chemical molecular species that provide markers for separation of these sources. Recent advances in chemical analytical techniques have facilitated the development of sophisticated molecular source profiles, including detailed speciation of organic compounds which allow the apportionment of particulate matter to gasoline and diesel sources with increased certainty. Older studies that made use of only elemental source profiles have been published and are summarized here, but are subject to more uncertainty. It should be noted that since receptor modeling is based on the application of source profiles to ambient measurements, the CMB estimates of diesel particulate matter concentrations do not distinguish between on-road and off-highway sources. In addition, this model accounts for primary emissions of diesel particulate matter only; the contribution of secondary aerosols is not included.

Dispersion models estimate ambient levels of particulate matter at a receptor site on the basis of emission factors for the relevant sources and the investigator's ability to model the advection, mixing, deposition, and chemical transformation of compounds from the source to the receptor site. Dispersion models can provide the ability to distinguish on-road from off-highway diesel sources and can be used to estimate the concentrations of secondary aerosols from diesel exhaust. Dispersion modeling is being conducted by EPA to estimate concentrations of, and exposures to several toxic species, including diesel particulate matter.

Elemental carbon (EC) is a major component of diesel particulate matter, contributing approximately 60 to 80 percent of diesel particulate mass, depending on engine technology, fuel type, duty cycle, lube oil consumption, and state of engine maintenance.^{28 29 30 31} In most ambient environments, diesel particulate matter is one of the major contributors to EC, with other potential sources including gasoline exhaust; combustion of coal, oil, or wood; charbroiling; cigarette smoke; and road dust. Because of the large portion of EC in diesel particulate matter, and the fact that diesel exhaust is one of the major contributors to EC in most ambient environments, diesel particulate matter concentrations can be bounded using EC measurements. One approach for calculating diesel particulate matter concentrations from EC measurements is presented in the draft *Health Assessment for Diesel Exhaust*.³² The surrogate diesel particulate matter calculation is a useful approach for estimating diesel particulate matter in the absence of a more sophisticated modeling analysis for locations where EC concentrations are available.

Annual average diesel particulate matter concentrations measured during or after 1988 in urban areas are generally greater than 0.6 micrograms/m³ and range up to 3.6 micrograms/m³ in the South Coast Air Basin and 2.4 micrograms/m³ in Phoenix, AZ (Table II.A-21). Diesel particulate matter concentrations measured on individual days in urban areas are as high as 46.7 micrograms/m³ in Manhattan, NY, 22 micrograms/m³ in Phoenix, AZ and 13.3 micrograms/m³ in Riverside, CA, the latter of which includes both primary and secondary diesel particulate matter. In two dispersion model studies in Southern California, secondary formation of diesel particulate matter accounted for 27 to 67 percent of the total diesel particulate matter concentrations on individual days of 2.6 micrograms/m³ and 13.3 micrograms/m³, respectively.^{33 34} Off-highway diesel engines also operate in urban areas, and may have contributed to the ambient diesel particulate matter concentrations reported for CMB studies, depending on the sampling location. Dispersion modeling conducted in Southern California reported that the on-road contribution to the reported diesel particulate matter levels ranged from 63-89 percent of the total diesel particulate matter.³⁵

Table II.A-21. Ambient Diesel Particulate Matter Concentrations from Receptor Modeling, Dispersion Modeling and Elemental Carbon Measurements

<i>Location</i>	<i>Year of Sampling</i>	<i>Diesel PM₁₀ & PM_{2.5} $\mu\text{g}/\text{m}^3$ (mean)</i>	<i>Diesel PM % of Total PM</i>	<i>Type of Data</i>
West LA, CA	1982, annual	4.4	18	Source-Receptor Model: Based on ambient measurements at receptor sites.
Pasadena, CA	1982, annual	5.3	19	
Rubidoux, CA	1982, annual	5.4	13	
Downtown LA, CA ³⁶	1982, annual	11.6	36	
Phoenix area, AZ ³⁷	1989-90, Winter	4-22 ^A	9-20	
Phoenix, AZ ³⁸	1994-95, Nov-	0-5.3 (2.4)	0-27 ^B	
California, 15 Air Basins ³⁹	1988-92, annual	0.2-3.6 ^A		
Manhattan, NY ⁴⁰	1993, Spring 3	13.2-46.7 ^A	31-68	
Welby, CO	1996-97, Winter 60 days	0-7.3 (1.7)	0-26	
Brighton, CO ⁴¹	1996-97, Winter 60 days	0-3.4 (1.2)	0-38	
Azusa, CA	1982, annual	1.4 ^D	5	Dispersion Model: Based on emission rates from the majority of PM sources contributing to the area studied.
Pasadena, CA	1982, annual	2.0 ^D	7	
Anaheim, CA	1982, annual	2.7 ^D	12	
Long Beach, CA	1982, annual	3.5 ^D	13	
Downtown LA, CA	1982, annual	3.5 ^D	11	
Lennox, CA	1982, annual	3.8 ^D	13	
West LA, CA ⁴²	1982, annual	3.8 ^D	16	
Claremont, CA ⁴³	18-19 Aug 1987	2.4 (4.0) ^{C D}	8	
Long Beach, CA	24 Sept 1996	1.9(2.6) ^C	8	
Fullerton, CA	24 Sept 1996	2.4(3.9) ^C	9	
Riverside, CA ⁴⁴	25 Sept 1996	4.4(13.3) ^C	12	
Boston, MA	1995, annual	0.8-1.7 (1.1)	6-12	Diesel PM based on EC measurements.
Rochester, NY ⁴⁵	1995, annual	0.4-0.8 (0.5)	3-6	
Washington, DC ⁴⁶	1992-1995,	1.0-2.2 (1.5)	5-12 ^B	
South Coast Air Basin ⁴⁷	1995-1996,	2.4-4.5 ^E		

^A PM₁₀. The reader should note that 80-95 percent of diesel PM is PM_{2.5}.

^B Not Available.

^C Value in parenthesis includes secondary diesel PM (nitrate, ammonium, sulfate and hydrocarbons) due to atmospheric reactions of primary diesel emissions of NO_x, SO₂ and hydrocarbons.

^D On-road diesel vehicles only; All other values are for on-road plus off-highway diesel emissions.

^E The Multiple Air Toxics Exposure Study in the South Coast Air Basin reported average annual values for 8 sites in the South Coast Basin.

In addition to these studies, investigations of the concentrations of diesel particulate matter in some microenvironments and “hotspot” areas have been conducted. One such study in Manhattan, NY collected ambient particulate matter near a bus stop on Madison Avenue during a three day period in 1993.⁴⁸ Source apportionment applied to these samples indicated that diesel particulate matter concentrations ranged from 13.2 to 46.7 micrograms/m³ and this study attributed, on average, 53 percent of the total PM₁₀ to diesel exhaust. Interpretation of the results of this study require some caution due to the methods used to apportion sources. Concentrations of diesel particulate matter in the vicinity of bus stops may be indicative of concentrations also experienced by urban dwellers who live and/or work in the vicinity of large on-road diesel emission sources and these concentrations may contribute significantly to exposures among some urban dwellers. Kinney et al. (2000) reported elemental carbon concentrations from personal monitors worn by study participants who were located on sidewalks at four intersections in Harlem, NY. The elemental carbon concentrations ranged from 1.5 micrograms/m³ to 6 micrograms/m³ and were reported to be associated with diesel bus and truck counts.

In an additional study to assess diesel particulate matter concentrations near heavily traveled roadways, the California Air Resources Board (ARB) collected data on ambient elemental carbon concentrations near the Long Beach Freeway for 3 days in December 1993.⁴⁹ Using emission estimates from their mobile source emissions model, and elemental/organic carbon composition profiles for diesel and gasoline exhaust, tire wear, and road dust, ARB estimated that the contribution of freeway diesel traffic resulted in diesel particulate matter concentrations ranging from 0.7 micrograms/m³ to 4.0 micrograms/m³ above background concentrations.

A study designed to investigate relationships between diesel exhaust exposure and respiratory health of children in the Netherlands found that schools within 400 meters of a freeway had average elemental carbon concentrations of 3.4 micrograms/m³, while schools more than 400 meters from freeways had average elemental carbon concentrations of 1.4 micrograms/m³.⁵⁰

Recently the South Coast Air Quality Management District completed their Multiple Air Toxics Exposure Study in the South Coast Air Basin (MATES-II) to investigate spatial differences in risk from air toxics exposures in the Basin.⁵¹ For this study, elemental carbon concentrations were measured as a surrogate for diesel particulate matter every sixth day for a one year period from April 1998 through March 1999 at eight locations throughout the South Coast Basin. Annual average elemental carbon concentrations ranged from 2.4 micrograms/m³ to 4.5 micrograms/m³ across the eight-site network. Monthly mean elemental carbon values peaked during winter months with maximum monthly elemental carbon reaching 13.4 micrograms/m³.

In a separate study, the California ARB measured elemental carbon concentrations in vehicles on Los Angeles roadways as a surrogate for diesel particulate matter. In-vehicle concentrations of diesel particulate matter are an important microenvironmental exposure for

many people.⁵² Diesel particulate matter concentrations in the vehicle were estimated to range from approximately 2.8 micrograms/m³ to 36.6 micrograms/m³ with the higher concentrations measured when the vehicle followed a HDDV.

ii. *Occupational and Population Exposures*

A distinction must be made between ambient concentrations and the concentration of diesel particulate matter to which people are exposed. Ambient concentrations reflect outdoor levels of diesel particulate while exposure depends on both the concentrations of diesel particulate matter and the time spent in various microenvironments where people are exposed. Since people typically spend a large portion of their day indoors and indoor diesel particulate matter concentrations are lower than outdoor concentrations (in the absence of an indoor diesel PM source), then the concentrations to which most people are exposed are expected to be lower than ambient diesel particulate matter concentrations. Exposure to diesel exhaust is most commonly measured in terms of diesel particulate matter and is reported as such in the following section. This information is summarized in the draft *Health Assessment for Diesel Exhaust* and briefly summarized here.

Exposure to diesel exhaust has been measured for several occupationally exposed groups including miners, railroad workers, diesel forklift operators, firefighters, truck drivers, dockworkers and mechanics. Diesel exhaust occupational exposures (typically measured as respirable dust) reported for workers in non-coal mines using diesel-powered shuttle cars range from approximately 38 to 1,280 micrograms/m³.^{53 54} Diesel exhaust exposures measured among railroad workers (as smoking-adjusted respirable particulate) ranged from 39 micrograms/m³ for engineers/firers, to 134 micrograms/m³ for locomotive shop workers and 191 micrograms/m³ for hostlers.⁵⁵ Diesel exhaust exposure among firefighters operating diesel engine vehicles ranges from 4-748 micrograms/m³ which also encompasses the range of diesel exhaust exposures reported for diesel forklift dockworkers (18.6-64.7 micrograms/m³).^{56 57 58 59} Diesel exhaust exposures measured for truck drivers, mechanics and dockworkers using elemental carbon as a surrogate for diesel particulate matter ranged from 2.0-7.0 micrograms/m³ for road and local truckers and from 4.8 to 28.0 micrograms/m³ for dockworkers and mechanics.⁶⁰

For several occupational categories, the occupational exposure and/or environmental equivalent of the occupational exposure overlap with some current ambient concentrations and also overlap with exposure estimates provided by the Hazardous Air Pollutant Exposure Model described below (Table II.A-22). The relevance of the comparison between estimated occupational exposures and ambient exposures to diesel exhaust is discussed in section d. Potential for Cancer Risk, below.

Table II.A-22. Occupational and Population Exposure to Diesel Exhaust

<i>Year of Sampling</i>	<i>Locations</i>	<i>Diesel PM, ug/m³</i>
Occupational Exposure for a Minimum 8-Hour Workday		
1980's	Non-coal Miners ^A	38 - 1,280
1980's	Railroad Workers ^B	39 - 191
1980's	Diesel Forklift Dockworkers ^C	9 - 61
1980 and 1990's	Firefighters/Fire Station Employees ^D	4-748
1990's	Public Transit Workers, Airport Ground Crew ^E	7-98
1990	Long- and Short-Haul Truckers, Dockworkers, Mechanics ^F	2 - 28
Ambient Exposure Estimates (On-Road) ^G		
1990	National Annual Average	0.84
1990	Urban Annual Average	0.92
1990	Urban Annual Average Outdoor Workers	1.1
1990	Range of Annual Average for Most Highly Exposed by City	0.83 - 4.0
California Exposure Estimates (On-Road & Nonroad) ^H		
1990	California Annual Average	2.1
1995	Projected California Annual Average	1.5
2000	Projected California Annual Average	1.3
2010	Projected California Annual Average	1.2

^A Watts (1995) and Säverin et al., (1999)

^B Woskie et al. (1988)

^C NIOSH (1990); Zaebst et al. (1991)

^D Friones et al. (1991); NIOSH (1992); Birch and Carey (1996)

^E Birch and Carey (1996)

^F Zaebst et al. (1991)

^G HAPEM-MS3 exposure results for 1990 for on-road sources only. Methodology is described below. These estimates are for the average population and the uncertainty associated with them is large. In particular, in areas where diesel vehicles comprise a higher-than-average portion of the vehicle fleet, exposures will be substantially higher than predicted average exposure estimates.

^H California EPA (1998).

To estimate population exposures to diesel particulate matter the EPA currently uses the Hazardous Air Pollutant Exposure Model - Mobile Source 3 (HAPEM-MS3).⁶¹ This model provides national and urban-area specific exposures to diesel particulate matter from on-road sources only. Results for 1990 are presented in Table II.A-22. Modeled atmospheric concentrations and exposure estimates of diesel PM from on-highway and nonroad sources have

recently been developed as part of the National Air Toxics Assessment (NATA) National-Scale Analysis. Results from the National-Scale Analysis are currently in draft form and are undergoing technical review by States and EPA's Scientific Advisory Board after which time the data may change. Information on the National-Scale Analysis can be found on the Agency's Urban Air Toxics Website.⁶² Table II.A-22 also includes exposure estimates for on-road and nonroad sources modeled by the California EPA's California Population Indoor Exposure Model (CPIEM). Results from this model are presented below and described in more detail in California ARB's "Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant Appendix III Part A: Exposure Assessment".⁶³

The HAPEM-MS3 model estimates personal exposures to diesel particulate matter using a ratio to ambient CO measurements. Since most ambient CO comes from motor vehicles, we believe CO exposure is a reasonable surrogate for exposure to other motor vehicle emissions, including emissions of toxic compounds. The HAPEM-MS3 model is based on the carbon monoxide (CO) probabilistic NAAQS exposure model (pNEM/CO), which is used to estimate the frequency distribution of population exposures to CO and the resulting carboxyhemoglobin levels. The pNEM/CO model has undergone evaluation and the results of this evaluation are considered applicable to HAPEM-MS3.⁶⁴ The HAPEM-MS3 model simulates the movement of individuals between home and work and through 37 microenvironments. CO concentrations are based on ambient measurements made in 1990 and are related to exposures of individuals in a ten km radius around the sampling site.

Exposure modeling was conducted for 1990. CO concentration data from ten urban areas were used to model 1990 exposures. These areas were Atlanta, GA, Chicago, IL, Denver, CO, Houston, TX, Minneapolis, MN, New York, NY, Philadelphia, PA, Phoenix, AZ, Spokane, WA, and St. Louis, MO. These areas were selected because a large percentage of the population lived within reasonable proximity to CO monitors, and also to represent good geographic coverage of the U.S. The HAPEM model links human activity patterns with ambient CO concentration to arrive at average exposure estimates for 22 different demographic groups (e.g., outdoor workers, children 0 to 17, working men 18 to 44, women 65+) and for the total population. The model simulates the movement of individuals between home and work and through a number of different microenvironments. The CO concentration in each microenvironment is determined by multiplying ambient concentration by a microenvironmental factor derived from regression analysis of ambient and personal monitor data. Each microenvironmental factor has a multiplicative term, which represents ambient exposure, and an additive term, which represents exposure to emissions originating within microenvironments. These factors were derived by IT Corporation using paired ambient and personal exposure monitor measurements from CO studies in Denver and Washington.^{65 66} In our modeling, we set the additive term to zero, to eliminate non-ambient sources of CO, such as gas stoves. The multiplicative term has a component that represents penetration from the ambient air into the microenvironment, and a factor that represents the proximity of the microenvironment to monitors. Thus, even though a compound may have a penetration of close to one, the microenvironmental factor could be significantly less

than one if the microenvironment is typically found a significant distance from where CO monitors are located.

With the 1990 CO exposure estimates generated by the HAPEM-MS3 model for each urban area, EPA determined the fraction of exposure that was a result of on-road motor vehicle emissions. This calculation was accomplished by scaling the exposure estimates (which reflect exposure to total ambient CO) by the fraction of the 1990 CO emissions inventory from on-road motor vehicles, determined from the EPA Emission Trends database.^{67 68} Nationwide urban CO exposure from on-road motor vehicles was estimated by first calculating a population-weighted average CO exposure for the ten modeled areas. This number was adjusted by applying a ratio of population-weighted annual average CO for urban areas in the entire country versus average ambient CO concentration for the modeled areas. To estimate rural exposure, the urban estimate was scaled downward using estimates of urban versus rural exposure from the 1993 *Motor Vehicle-Related Air Toxics Study*.⁶⁹

Motor vehicle diesel particulate matter and CO emission rates reported by EPA⁷⁰ are used to calculate mobile source diesel particulate matter exposures. Methods for the development of particulate matter emissions used to calculate population exposures can be found in “Analysis of the Impacts of Control Programs on Motor Vehicle Toxic Emissions and Exposure in Urban Areas and Nationwide: Volumes I and II”.⁷¹ Diesel particulate matter (DPM) exposures are calculated as in Equation 1, using a ratiometric approach to CO.

$$DPM_{ug/m^3} = (CO_{ug/m^3} / CO_{g/mi}) \times DPM_{g/mi}$$

Equation 1. Ratiometric Calculation of Diesel Particulate Matter Based on CO Exposures.

To estimate diesel particulate matter emissions, we used EPA’s PART5 model. PART5 is similar in structure and function to the MOBILE series of models and calculates exhaust and non-exhaust (e.g., road dust) particulate emissions for each vehicle class included in the MOBILE models. PART5 is currently being modified to account for deterioration, in-use emissions, poor maintenance and tampering effects, all of which would increase emission factors. As a result, we believe that HAPEM-MS3 exposure estimates, based on PART5 emission factors, may underestimate true exposures. A comparison of PART5 HDDV emission factors with a comprehensive review of HDDV emission factors reported from in-use chassis dynamometer testing⁷² and modeling performed by CARB suggests that PART5 may underestimate HDDV emissions by up to 50 percent. Diesel PM exposures reported here were adjusted to account for new data demonstrating higher HDDV VMT compared with the HDDV VMT presented in the “Analysis of the Impacts of Control Programs on Motor Vehicle Toxic Emissions and Exposure in Urban Areas and Nationwide: Volumes I and II”. A complete description of the HAPEM-MS3 model can be found in “Final Technical Report on the Analysis of Carbon Monoxide Exposure for Fourteen Cities Using HAPEM-MS3”.⁷³

Our methodology for modeling exposure to diesel particulate matter using HAPEM-MS3 has certain limitations and uncertainties. Our use of HAPEM-MS3 to estimate population exposures to air toxics was peer reviewed for the 1993 Motor Vehicle Related Air Toxics Study⁷⁴ and more recently for the EPA (1999) report summarized here.^{75 76 77} Important aspects of our modeling approach are addressed in these comments and are summarized briefly here.

A validation study conducted for the pNEM/CO model on which HAPEM-MS3 is based, indicates that CO exposures for the population in the 5th percentile were overestimated by approximately 33 percent, while those with exposures in the 98th percentile were underestimated by about 30 percent. Based on this finding, we expect that HAPEM-MS3 also underestimates exposures in the highly exposed populations. To assess exposures for highly exposed populations, we have used 1990 CO concentrations relevant to the most highly exposed populations to estimate 1990 diesel particulate matter exposures for different demographic groups in this population.⁷⁸

Two aspects of the HAPEM-MS3 model which result in some uncertainty in diesel particulate matter exposure estimates are: 1) HAPEM-MS3 assumes that the highway fleet (gasoline plus diesel) emissions ratio of CO to diesel particulate matter can be used as an adjustment factor to convert estimated CO personal exposure to diesel particulate matter exposure estimates; and 2) the model does not account for physical and chemical differences between diesel particulate matter and CO. Even though gasoline vehicles emit the large majority of CO, gasoline and diesel highway vehicles travel on the same roadways and we are making the assumption that diesel vehicles will comprise a constant fraction of on-road traffic. Diesel particulate matter and CO are both relatively long-lived atmospheric species (1-3 days) except under certain conditions such as precipitation which will more readily remove particulate matter. Our exposure modeling assumes that for the average person in a modeled air district, CO and diesel particulate matter are well mixed. We are not attempting to assess exposure in microscale environments in which these assumptions may not be valid. While our assumptions have inherent uncertainties, we find that exposure estimates provided by the HAPEM-MS3 model are lower than the majority of ambient diesel particulate matter concentrations. This comparison provides some indication that HAPEM-MS3 exposure estimates are in the range of reasonable exposure estimates for the average population. It is noteworthy that these exposure estimates underestimate exposures for the more highly exposed populations in part due to the underestimate of CO exposures in the 98th percentile (discussed above), underestimates of emission factors by PART5, and the inability to assess small spatial and temporal scale environments.

While EPA continues efforts toward improving exposure estimates, the results of current HAPEM-MS3 exposure modeling are used here to compare exposure ranges to ambient concentration data for the purposes of characterizing potential environmental risk.

Diesel particulate matter exposure was assessed by on-road vehicle class and found to be due almost entirely to emissions from HDDVs. Nationally in 1996, 99 percent of diesel

particulate matter exposure from on-road vehicles is attributable to HDDVs and the rest is generated mainly by LDDTs. We estimate that in 1990, exposure to diesel particulate matter ranged from 0.84 micrograms/m³ for the general population to 1.1 micrograms/m³ for outdoor workers (Table II.A-22). Since HDDV traffic, and therefore exposure to diesel particulate matter, varies for different urban areas, we used HAPEM-MS3 to estimate annual average population exposures for ten urban areas.⁷⁹ Modeled 1990 diesel particulate matter exposures in Minneapolis, MN (1.0 micrograms/m³), New York, NY (1.6 micrograms/m³), Phoenix, AZ (1.3 micrograms/m³), and Spokane, WA (1.2 micrograms/m³) were all higher than the 1990 urban exposure average of 0.92 micrograms/m³ for 1990.^{aa}

Since HAPEM-MS3 is suspected to underestimate exposures in the highly exposed populations, we have used 1990 CO concentrations relevant to the most highly exposed populations to estimate 1990 diesel particulate matter exposures for different demographic groups in this population.⁸⁰ The highest estimated diesel particulate matter exposures ranged up to 4.0 micrograms/m³ for outdoor children in New York. The highest exposed demographic groups were those who spend a large portion of their time outdoors. It is important to note that these exposure estimates are lower than the total exposure to diesel particulate matter since they reflect only diesel particulate matter from on-road sources.

Annual average exposure to on-road HDDV particulate matter was modeled for 1990 and 1996. We expect annual average nationwide exposures to change proportionally with the change in the PM emissions inventory. These estimates are for the average population and the uncertainty associated with them is significant. In particular, in areas where diesel vehicles comprise a higher-than-average portion of the vehicle fleet, exposures may be substantially higher than predicted average exposure estimates.

The exposure estimates using HAPEM-MS3 are substantially lower than those reported by California EPA which range from 1.5 micrograms/m³ in 1995, to 1.3 micrograms/m³ in 2000.⁸¹ One significant reason for the difference is that the California estimate is for diesel PM₁₀ from all sources, including off-highway, while HAPEM estimates exposures for highway vehicles only. Other reasons may be differences in estimates of emission rates, exposure patterns, the concentration of diesel vehicle traffic, or the spatial distribution of diesel engine emissions.

HAPEM-MS3 exposure estimates for the general population are also lower than annual average diesel particulate matter concentrations reported from most receptor and dispersion models. We have modeled exposure for two urban areas for which there is an estimate of ambient diesel particulate concentrations (Phoenix, AZ and Denver, CO). In these locations, the annual average exposure estimates are up to a factor of two lower than ambient concentrations.

^{aa} Memorandum to air docket, May 1, 2000, Determination of demographic groups with the highest annual averaged modeled diesel PM exposure. Pamela Brodowicz, Office of Transportation and Air Quality.

For example, the modeled annual average exposure for the general population in Phoenix in 1996 is $1.3 \mu\text{g}/\text{m}^3$ and recent sampling conducted in 1994-1995 in Phoenix indicates that concentrations of diesel particulate matter are $2.4 \text{ micrograms}/\text{m}^3$. In Denver, CO the 1996 exposure estimate for the general population is $0.8 \text{ micrograms}/\text{m}^3$ and the winter sampling conducted during the Northern Front Range Air Quality Study indicates that in Welby and Brighton, CO, average ambient concentrations of diesel particulate matter are $1.7 \text{ micrograms}/\text{m}^3$ and $1.2 \text{ micrograms}/\text{m}^3$, respectively. This difference in exposure estimates and ambient concentrations is expected since a large portion of time is spent indoors by most people (where diesel PM concentrations are lower than outdoors) and the HAPEM-MS3 exposure estimates do not include the influence of off-highway sources of diesel particulate matter. Our emissions inventory suggests that mobile sources account for approximately 98 percent of all diesel particulate matter emissions and that on-road HDDVs emit approximately one-third of the diesel particulate matter with the rest attributable to off-highway equipment.⁸² Reductions in on-road diesel particulate matter emissions resulting from today's action will have a substantial impact on population exposure to diesel particulate matter.

The discrepancy between exposure and ambient concentrations is small for those who spend a large portion of their day out-of-doors or for those whose microenvironmental exposures permit greater intrusion of outdoor air (such as those whose occupations require that they spend substantial time in motor vehicles). For these more highly exposed demographic groups HAPEM-MS3 still underestimates exposure. Given the ambient concentration data available from some hotspot studies, exposure to diesel particulate matter for the highly exposed subset could be quite large and is likely to overlap some occupational exposures to a large degree.

d. Potential for Cancer Risk

The EPA has concluded that diesel exhaust is likely to be carcinogenic to humans by inhalation at occupational and ambient levels of exposure. While the available evidence leads to EPA's conclusion that diesel exhaust is a likely human lung carcinogen, the evidence is insufficient to develop a confident estimate of cancer unit risk. The absence of quantitative estimates of the lung cancer unit risk for diesel exhaust limits our ability to characterize the precise magnitude of the cancer impact. Given the absence of a unit risk estimate, we provide a perspective on the possible risks to gain a better understanding of the potential significance of the cancer hazard for the general population.

With respect to the estimation of a unit risk for diesel exhaust, risk assessments using epidemiological studies in the peer-reviewed literature which have attempted to assess the lifetime risk of lung cancer in workers occupationally exposed to diesel exhaust suggest that lung cancer risk may range from 10^{-4} to 10^{-2} .^{83 84 85} The Agency recognizes the significant uncertainties in these studies, and has not used these estimates to assess the possible cancer unit risk associated with ambient exposure to diesel exhaust.

In the draft Assessment, EPA acknowledged the limitations in confidently characterizing a unit risk and provided a discussion of the possible cancer risk consistent with occupational epidemiological findings of increased risk and relative exposure ranges in the occupational and environmental settings. Such an approach does not produce estimates of cancer unit risk. Rather, this approach provides a perspective on the possible magnitude of environmental cancer risk and thus insight about the possible significance of the hazard. We describe here two approaches to gauge the magnitude of potential cancer risk from ambient exposure to diesel exhaust. A more complete description of the approaches and the methods used can be found in the draft Assessment.

One approach to provide a perspective on the possible magnitude of the environmental cancer risk involves examining the differences between the levels of occupational and ambient exposures, and assuming that cancer risk posed by exposure to diesel exhaust is linearly proportional with cumulative lifetime exposure. Risks to the general public are considered to be of concern if the differences between occupational and ambient exposure are small (i.e., within one to two orders of magnitude), as they would approach workers' risk as observed in epidemiologic studies of past occupational exposures.

To compare differences between occupational and ambient exposures, it is necessary to convert occupational exposure estimates to continuous exposure (e.g., an environmental equivalent exposure). The relationship between occupational exposure and environmental equivalent exposure is calculated based on a typical set of assumptions to account for the difference between the amount of air breathed by a worker during their working lifetime compared to an individual in the general population during their 70-year lifetime (environmental equivalent exposure = $0.21 \times$ occupational exposure).^{bb} The environmental equivalent exposures for the occupational exposures presented in Table II.A-23 range from 0.4 to 269 micrograms/m³.

The environmental equivalent exposure is then compared to ambient diesel exhaust exposure by calculating an exposure margin (EM) which is the ratio of the environmental equivalent exposure to ambient exposure. Table II.A-23 presents the ratios of environmental equivalent exposure to ambient exposures. An EM of one or less indicates that ambient exposure is comparable to occupational exposure (expressed as the environmental equivalent exposure). An EM greater than one means that the occupational exposure is greater than the ambient exposure. Table II.A-23 shows that the EMs based on the average nationwide ambient exposure ($0.84 \mu\text{g}/\text{m}^3$) may be less than one for low-end occupational exposure and start to approach three orders of magnitude for high end occupational exposure. The EMs based on a high-end ambient exposure (i.e., $4.0 \mu\text{g}/\text{m}^3$) range from less than one to less than two orders of magnitude. This exposure analysis only addresses on-road sources for DE exposure. With additional diesel

^{bb} The fraction of a worker exposure relevant to a 70-year lifetime exposure is typically calculated by multiplying the fraction of air inhaled during a typical work shift by the fraction of a week, year and life during which a worker is exposed: $(10\text{m}^3/\text{shift} / 20\text{m}^3/\text{day}) * (5 \text{ days} / 7\text{days}) * (48 \text{ weeks} / 52 \text{ weeks}) * (45 \text{ years} / 70 \text{ years}) = 0.21$.

exhaust exposures from nonroad sources, there is a potential small margin of exposure and hence a greater concern for diesel exhaust-induced cancer risk.

Table II.A-23. Occupational and Population Exposure to Diesel Exhaust, Environmental Equivalent Exposures and Exposure Margins

Occupational Group	Estimated Occupational Exposure, $\mu\text{g}/\text{m}^3$	Environmental Equivalent Exposure, $\mu\text{g}/\text{m}^3$	Exposure margin ratio using 0.84 $\mu\text{g}/\text{m}^3$ ambient exposure	Exposure margin ratio using 4.0 $\mu\text{g}/\text{m}^3$ ambient exposure
Non-coal Miners ^A	38-1,280	8-269	10-320	2-67
U.S. Railroad Workers ^B	39-191	8-40	10-48	2-10
Firefighters ^C	4-748	0.8-157	1-187	0.2-39
Public Transit Workers, Dockworkers ^D	2-98	0.4-21	0.5-25	0.1-5

^A Watts (1995) and Säverin et al., (1999).

^B Woskie et al. (1988).

^C Friones et al. (1991); NIOSH (1992); Birch and Carey (1996).

^D Birch and Carey (1996); Zaebst et al. (1991); NIOSH (1990).

The potential overlap and small margins between occupational and ambient diesel exhaust exposures demonstrated in this analysis, is a significant public health concern for an environmental pollutant that is viewed as a likely human carcinogen. Several factors including the carcinogenicity of diesel, differences in human susceptibility, and our current lack of information regarding exposure to diesel exhaust from non-road sources all affirm the Agency's concern regarding the small difference between ambient concentrations and exposures and occupational exposure levels where the presence of diesel exhaust correlates with an increased risk of lung cancer.

To further characterize the significance of the potential environmental cancer hazard, the Agency is using a three step process based on general epidemiological principles to evaluate the available information. First, the risk of excess lung cancer attributed to occupational exposure to diesel exhaust is estimated. Second, the exposure margin between occupational and ambient exposures is considered. Finally, a perspective on the diesel exhaust hazard significance is derived by proportioning the excess risk from step one by the diesel exhaust exposure margins provided from step two. This approach is expanded upon below and is explained in more detail in the draft Assessment.⁸⁶

In its review of the published literature, EPA found that about 30 individual epidemiological studies show increased lung cancer risk associated with diesel emissions. In the draft Assessment EPA evaluated 22 studies that were the most relevant for risk assessment, 16 of which reported significant increased lung cancer risks, ranging from 20 to 167 percent, associated with diesel exhaust exposure. Questions remain about the influence of other factors (e.g., effect of smoking, other particulate sources), the quality of the individual epidemiologic studies, exposure levels, and consequently the precise magnitude of the increased risk of lung cancer. Two published analytic studies pooled many of the 30 individual epidemiological studies and after adjusting for smoking reported a relative risk increase of 1.35 and 1.47.^{87 88} For the purpose of this analysis, we have used these pooled studies to select a relative risk of 1.4 as a reasonable estimate of the increased lung cancer attributed to exposure to diesel exhaust in occupational settings.

The relative risk of 1.4 means that the occupationally exposed workers experienced an extra risk that is 40 percent higher than the 5 percent background lifetime lung cancer risk in the U.S. population.^{cc} Thus, using the relationship [*excess risk* = (*relative risk* - 1) × *background risk*], the diesel exhaust-exposed workers would have an excess risk of developing lung cancer of 2 percent (10^{-2}) due to occupational exposure to diesel exhaust [(1.4 - 1) × 0.05] = 0.02]. In this analysis, we refer to this value as the occupational population risk.^{dd} This is not a unit risk value.

Since the risk is assumed to be proportional to cumulative lifetime exposure, lower exposures among the general population compared to the occupational population, decrease the occupational population risk proportionally. As discussed above, occupational and ambient exposure estimates indicate that the exposure margins (i.e., the EM ratio) between occupational and ambient exposures may range from 0.5-320 when comparing occupational environmental equivalent exposure to the nationwide average ambient exposure of $0.84 \mu\text{g}/\text{m}^3$. If lifetime risks decrease proportionately with reduced exposure, and if one assumes that past occupational exposures were at the high end, then the risk from average ambient exposure could be between 10^{-5} and 10^{-4} ($0.02 \div 320 = 6 \times 10^{-5}$). If occupational exposures were closer to $50 \mu\text{g}/\text{m}^3$, a value

^{cc} The background rate of 0.05 is an approximated lifetime risk calculated by the method of lifetable analysis using age-specific lung cancer mortality data and probability of death in the age group taken from the National Health Statistics (HRS) monographs of Vital Statistics of the U.S. (Vol. 2, Part A, 1992). Similar values based on two rather crude approaches can also be obtained: (1) $59.8 \times 10^{-5} / 8.8 \times 10^{-3} = 6.8 \times 10^{-2}$ where 59.8×10^{-5} and 8.8×10^{-3} are respectively the crude estimates of lung cancer deaths (including intrathoracic organs, estimated to be less than 105 of the total cases) and total deaths for 1996 reported in Statistical Abstract of the U.S. (Bureau of the Census, 1998, 118th Edition), and (2) $156,900/270,000,000 \times 76 = 0.045$, where 156,900 is the projected lung cancer deaths for the year 2000 as reported in Cancer Statistics 9J of American Cancer Society, Jan/Feb 2000), 270,000,000 is the current U.S. population, and 76 is the expected lifespan.

^{dd} As used in this document, population risk is defined as the risk (i.e. a mathematical probability) that lung cancer might be observed in the population after a lifetime exposure to diesel exhaust. Exposure levels may be occupational lifetime or environmental lifetime exposures. A population risk in the magnitude of 10^{-2} translates as the risk of lung cancer being evidenced in one person in one hundred over a lifetime exposure.

that is represented in several data sets shown in Table II.A-23 (with an equivalent environmental exposure of $11 \mu\text{g}/\text{m}^3$ and a corresponding EM of 13), then risks from ambient exposure would approach 10^{-3} ($0.02 \div 13 = 2 \times 10^{-3}$).

This analysis establishes a reasonable basis for concern that the general population faces possible lifetime environmental cancer risk ranging from 10^{-5} to 10^{-3} . Adding to this concern is recognition that segments of the population may be additionally exposed to nonroad sources of diesel exhaust which would increase the risk.

The environmental risk estimates included in the Agency's risk perspective are meant only to gauge the possible magnitude of risk to provide a means to understand the potential significance of the lung cancer hazard. The conversion of relative risk to population risk is not specific to the diesel exhaust data as it would apply to any pollutant exposure for which cancer risk increases are observed and there is a known background rate for the cancer in question. The environmental risk estimates are not to be construed as cancer unit risk estimates and are not suitable for use in analyses which would estimate possible lung cancer cases in exposed populations.

EPA recognizes that, as in all such risk assessments, there are uncertainties in the assessment of an environmental risk range. For diesel exhaust, these uncertainties include limitations in exposure data, uncertainty with respect to the most accurate characterization of the risk increases observed in the occupational epidemiological studies, chemical changes in diesel exhaust over time, and extrapolation of the risk from occupational to ambient exposures. As with any such risk assessment for a carcinogen, despite EPA's thorough examination of the available epidemiologic evidence and exposure information, at this time EPA can not rule out the possibility that the lower end of the risk range includes zero.^{ee} However, it is the Agency's best scientific judgement that the assumptions and other elements of this analysis are reasonable and appropriate for identifying the risk potential based on the scientific information currently available.

The Agency believes that the risk estimation techniques that were used in the draft Assessment to gauge the potential for and possible magnitude of risk are reasonable and the CASAC panel has concurred with the Assessment's discussion of the possible environmental

^{ee} EPA's scientific judgment (which CASAC has supported) is that diesel exhaust is likely to be carcinogenic to humans. Notably, similar scientific judgements about the carcinogenicity of diesel exhaust have been recently made by the National Toxicology Program of the Department of Health and Human Services, NIOSH, WHO, and OEHA of the State of California. In the risk perspective discussed above, EPA recognizes the possibility that the lower end of the environmental risk range includes zero. The risks could be zero because (1) some individuals within the population may have a high tolerance level to exposure from diesel exhaust and therefore are not susceptible to the cancer risks from environmental exposure and (2) although EPA has not seen evidence of this, there could be a threshold of exposure below which there is no cancer risk.

risk range with an understanding that some clarifications and caveats would be added to the final version of the Assessment.

In the absence of having a unit cancer risk to assess environmental risk, EPA has considered the relevant epidemiological studies and principles for their assessment, the risk from occupational exposure as assessed by others, and relative exposure differences between occupational and ambient levels of diesel exhaust exposure.

While uncertainty exists in estimating the possible magnitude of the environmental risk range, the likely hazard to humans together with the potential for significant environmental risks leads the Agency to believe that diesel exhaust emissions should be reduced in order to protect the public's health. We believe that this is a prudent measure in light of:

- the designation that diesel exhaust is likely to be carcinogenic to humans,• the exposure of the entire population to various levels of diesel exhaust,
- the consistent observation of significantly increased lung cancer risk in workers exposed to diesel exhaust, and
- the potential overlap and/or relatively small difference between some occupational settings where increased lung cancer risk is reported and ambient exposures.

Today's action will reduce exposure to the toxic gaseous component of diesel exhaust as a result of the NMHC standard and we expect that the particulate matter standard in today's action will result in the implementation of particulate matter control technology (catalyzed particulate traps) that will significantly reduce particulate matter and additionally remove gaseous hydrocarbons.

5. Gaseous Air Toxics

This section summarizes our analysis of the impact of the proposed HDV standards on exposure to gaseous air toxics. Heavy-duty vehicle emissions contain several substances that are known, likely, or possible human or animal carcinogens, or that have serious noncancer health effects. These substances include, but are not limited to, benzene, formaldehyde, acetaldehyde, 1,3-butadiene, acrolein, and dioxin. For the purposes of the exposure estimates presented in this section, we have chosen to focus on those compounds in heavy duty vehicle exhaust that are known, likely, or possible carcinogens and that have significant emissions from heavy-duty vehicles.

a. Health Effects

i. Benzene

Highway mobile sources account for 48 percent of nationwide emissions of benzene and HDVs account for 7 percent of all highway vehicle benzene emissions.⁸⁹ Benzene is an aromatic hydrocarbon which is present as a gas in both exhaust and evaporative emissions from motor vehicles. Benzene in the exhaust, expressed as a percentage of total organic gases (TOG), varies depending on control technology (e.g., type of catalyst) and the levels of benzene and other aromatics in the fuel, but is generally about three to five percent. The benzene fraction of evaporative emissions depends on control technology and fuel composition and characteristics (e.g., benzene level and the evaporation rate) and is generally about one percent.⁹⁰

The EPA has recently reconfirmed that benzene is a known human carcinogen by all routes of exposure.⁹¹ Respiration is the major source of human exposure. Long-term respiratory exposure to high levels of ambient benzene concentrations has been shown to cause cancer of the tissues that form white blood cells. Among these are acute nonlymphocytic leukemia,^{ff} chronic lymphocytic leukemia and possibly multiple myeloma (primary malignant tumors in the bone marrow), although the evidence for the latter has decreased with more recent studies.^{92,93} Leukemias, lymphomas, and other tumor types have been observed in experimental animals exposed to benzene by inhalation or oral administration. Exposure to benzene and/or its metabolites has also been linked with genetic changes in humans and animals⁹⁴ and increased proliferation of mouse bone marrow cells.⁹⁵ The occurrence of certain chromosomal changes in individuals with known exposure to benzene may serve as a marker for those at risk for contracting leukemia.⁹⁶

The latest assessment by EPA places the excess risk of developing acute nonlymphocytic leukemia at 2.2×10^{-6} to $7.7 \times 10^{-6}/\mu\text{g}/\text{m}^3$. There is a risk of about two to eight excess acute nonlymphocytic leukemia cases in one million people exposed to $1\mu\text{g}/\text{m}^3$ over a lifetime (70 years).⁹⁷ This range of unit risk represents the maximum likelihood (MLE) estimate of risk, not an upper confidence limit (UCL).

^{ff} Leukemia is a blood disease in which the white blood cells are abnormal in type or number. Leukemia may be divided into nonlymphocytic (granulocytic) leukemias and lymphocytic leukemias. Nonlymphocytic leukemia generally involves the types of white blood cells (leukocytes) that are involved in engulfing, killing, and digesting bacteria and other parasites (phagocytosis) as well as releasing chemicals involved in allergic and immune responses. This type of leukemia may also involve erythroblastic cell types (immature red blood cells). Lymphocytic leukemia involves the lymphocyte type of white blood cells that are responsible for the immune responses. Both nonlymphocytic and lymphocytic leukemia may, in turn, be separated into acute (rapid and fatal) and chronic (lingering, lasting) forms. For example; in acute myeloid leukemia (AML) there is diminished production of normal red blood cells (erythrocytes), granulocytes, and platelets (control clotting) which leads to death by anemia, infection, or hemorrhage. These events can be rapid. In chronic myeloid leukemia (CML) the leukemic cells retain the ability to differentiate (i.e., be responsive to stimulatory factors) and perform function; later there is a loss of the ability to respond.

A number of adverse noncancer health effects, blood disorders such as preleukemia and aplastic anemia, have also been associated with low-dose, long-term exposure to benzene.⁹⁸ People with long-term exposure to benzene may experience harmful effects on the blood-forming tissues, especially the bone marrow. These effects can disrupt normal blood production and cause a decrease in important blood components, such as red blood cells and blood platelets, leading to anemia (a reduction in the number of red blood cells), leukopenia (a reduction in the number of white blood cells), or thrombocytopenia (a reduction in the number of blood platelets, thus reducing the ability for blood to clot). Chronic inhalation exposure to benzene in humans and animals results in pancytopenia,^{gg} a condition characterized by decreased numbers of circulating erythrocytes (red blood cells), leukocytes (white blood cells), and thrombocytes (blood platelets).^{99,100} Individuals that develop pancytopenia and have continued exposure to benzene may develop aplastic anemia,^{hh} whereas others exhibit both pancytopenia and bone marrow hyperplasia (excessive cell formation), a condition that may indicate a preleukemic state.^{101 102} The most sensitive noncancer effect observed in humans is the depression of absolute lymphocyte counts in the circulating blood.¹⁰³

ii. *1,3-Butadiene*

Highway mobile sources account for approximately 42 percent of the annual emissions of 1,3-butadiene and HDVs account for approximately 15 percent of the highway vehicle portion.¹⁰⁴ 1,3-Butadiene is formed in vehicle exhaust by the incomplete combustion of fuel. It is not present in vehicle evaporative emissions, because it is not present in any appreciable amount in fuel. 1,3-Butadiene accounts for 0.4 to 1.0 percent of total organic gas exhaust, depending on control technology and fuel composition.¹⁰⁵

1,3-Butadiene was classified by EPA as a Group B2 (probable human) carcinogen in 1985.¹⁰⁶ This classification was based on evidence from two species of rodents and epidemiologic data. In the EPA 1998 draft Health Risk Assessment of 1,3-Butadiene, that was reviewed by the Science Advisory Board (SAB), the EPA proposed that 1,3-butadiene is a known human carcinogen based on human epidemiologic, laboratory animal data, and supporting data

^{gg} Pancytopenia is the reduction in the number of all three major types of blood cells (erythrocytes, or red blood cells, thrombocytes, or platelets, and leukocytes, or white blood cells). In adults, all three major types of blood cells are produced in the bone marrow of the vertebra, sternum, ribs, and pelvis. The bone marrow contains immature cells, known as multipotent myeloid stem cells, that later differentiate into the various mature blood cells. Pancytopenia results from a reduction in the ability of the red bone marrow to produce adequate numbers of these mature blood cells.

^{hh} Aplastic anemia is a more severe blood disease and occurs when the bone marrow ceases to function, i.e., these stem cells never reach maturity. The depression in bone marrow function occurs in two stages - hyperplasia, or increased synthesis of blood cell elements, followed by hypoplasia, or decreased synthesis. As the disease progresses, the bone marrow decreases functioning. This myeloplasmic dysplasia (formation of abnormal tissue) without acute leukemia is known as preleukemia. The aplastic anemia can progress to AML (acute myelogenous leukemia).

such as the genotoxicity of 1,3-butadiene metabolites.¹⁰⁷ The Environmental Health Committee of EPA's Scientific Advisory Board (SAB), reviewed the draft document in August 1998 and recommended that 1,3-butadiene be classified as a probable human carcinogen, stating that designation of 1,3-butadiene as a known human carcinogen should be based on observational studies in humans, without regard to mechanistic or other information.¹⁰⁸ In applying the 1996 proposed Guidelines for Carcinogen Risk Assessment, the Agency relies on both observational studies in humans as well as experimental evidence demonstrating causality and therefore the designation of 1,3-butadiene as a known human carcinogen remains applicable.¹⁰⁹ The Agency has revised the draft Health Risk Assessment of 1,3-Butadiene based on the SAB and public comments. The draft Health Risk Assessment of 1,3-Butadiene will undergo the Agency consensus review, during which time additional changes may be made prior to its public release and placement on the Integrated Risk Information System (IRIS).

The SAB panel recommended that EPA calculate the lifetime cancer risk estimates based on the human data from Delzell et al. 1995¹¹⁰ and account for the highest exposure of "360 ppm-year" for 70 years. Based on this calculation¹¹¹ the maximum likelihood estimate of lifetime cancer risk from continuous 1,3-butadiene exposure is 2.21×10^{-6} /microgram/m³. This estimate implies that approximately 2 people in one million exposed to 1 microgram/m³ 1,3-butadiene continuously for their lifetime (70 years) would develop cancer as a result of their exposure.

An adjustment factor of 3 can be applied to this potency estimate to reflect evidence from rodent studies suggesting that extrapolating the excess risk of leukemia in a male-only occupational cohort may underestimate the total cancer risk from 1,3-butadiene exposure in the general population.¹¹² First, studies in both rats and mice indicate that 1,3-butadiene is a multi-site carcinogen. It is possible that humans exposed to 1,3-butadiene may also be at risk of cancers other than leukemia and that the epidemiologic study had insufficient power to detect excess cancer risks for other tissues or sites in the body. Second, both the rat and mouse studies suggest that females are more sensitive to 1,3-butadiene-induced carcinogenicity than males, and the female mammary gland was the only 1,3-butadiene-related tumor site common to both species. Use of a 3-fold adjustment to the potency estimate of 2.21×10^{-6} /microgram/m³ derived from the occupational epidemiologic study yields a upper bound cancer potency estimate of 1.4×10^{-5} /microgram/m³, which roughly corresponds to a combination of the human leukemia and mouse mammary gland tumor risk estimates, at least partially addressing the concerns that the leukemia risk estimated from the occupational data may underestimate total cancer risk to the general population, in particular females.

1,3-Butadiene also causes a variety of noncancer reproductive and developmental effects in mice and rats (no human data) when exposed to long-term, low doses of butadiene.¹¹³ The most sensitive effect was reduced litter size at birth and at weaning. These effects were observed in studies in which male mice exposed to 1,3-butadiene were mated with unexposed females. In humans, such an effect might manifest itself as an increased risk of spontaneous abortions, miscarriages, still births, or very early deaths. Long-term exposures to 1,3-butadiene should be kept below its reference concentration of 4.0 microgram/m³ to avoid appreciable risks of these

reproductive and developmental effects.¹¹⁴ EPA has developed a draft chronic, subchronic, and acute RfC values for 1,3-butadiene exposure as part of the draft risk characterization mentioned above. The RfC values will be reported on IRIS.

iii. Formaldehyde

Highway mobile sources contribute approximately 24 percent of the national emissions of formaldehyde, and HDVs account for approximately 36 percent of the highway portion.¹¹⁵ Formaldehyde is the most prevalent aldehyde in vehicle exhaust. It is formed from incomplete combustion of both gasoline and diesel fuel and accounts for one to four percent of total organic gaseous emissions, depending on control technology and fuel composition. It is not found in evaporative emissions.

Formaldehyde exhibits extremely complex atmospheric behavior.¹¹⁶ It is formed by the atmospheric oxidation of virtually all organic species, including biogenic (produced by a living organism) hydrocarbons. Mobile sources contribute both primary formaldehyde (emitted directly from motor vehicles) and secondary formaldehyde (formed from photooxidation of other VOCs emitted from vehicles).

EPA has classified formaldehyde as a probable human carcinogen based on limited evidence for carcinogenicity in humans and sufficient evidence of carcinogenicity in animal studies, rats, mice, hamsters, and monkeys.¹¹⁷ Epidemiological studies in occupationally exposed workers suggest that long-term inhalation of formaldehyde may be associated with tumors of the nasopharyngeal cavity (generally the area at the back of the mouth near the nose), nasal cavity, and sinus. Studies in experimental animals provide sufficient evidence that long-term inhalation exposure to formaldehyde causes an increase in the incidence of squamous (epithelial) cell carcinomas (tumors) of the nasal cavity. The distribution of nasal tumors in rats suggests that not only regional exposure but also local tissue susceptibility may be important for the distribution of formaldehyde-induced tumors.¹¹⁸ Research has demonstrated that formaldehyde produces mutagenic activity in cell cultures.¹¹⁹

The MLE estimate of a lifetime extra cancer risk from continuous formaldehyde exposure is about $1.3 \times 10^{-6}/\mu\text{g}/\text{m}^3$. In other words, it is estimated that approximately 1 person in one million exposed to $1 \mu\text{g}/\text{m}^3$ formaldehyde continuously for their lifetime (70 years) would develop cancer as a result of this exposure. The agency is currently conducting a reassessment of risk from inhalation exposure to formaldehyde.

Formaldehyde exposure also causes a range of noncancer health effects. At low concentrations (0.05-2.0 ppm), irritation of the eyes (tearing of the eyes and increased blinking) and mucous membranes is the principal effect observed in humans. At exposure to 1-11 ppm, other human upper respiratory effects associated with acute formaldehyde exposure include a dry or sore throat, and a tingling sensation of the nose. Sensitive individuals may experience these effects at lower concentrations. Forty percent of formaldehyde-producing factory workers

reported nasal symptoms such as rhinitis (inflammation of the nasal membrane), nasal obstruction, and nasal discharge following chronic exposure.¹²⁰ In persons with bronchial asthma, the upper respiratory irritation caused by formaldehyde can precipitate an acute asthmatic attack, sometimes at concentrations below 5 ppm.¹²¹ Formaldehyde exposure may also cause bronchial asthma-like symptoms in non-asthmatics.^{122 123}

Immune stimulation may occur following formaldehyde exposure, although conclusive evidence is not available. Also, little is known about formaldehyde's effect on the central nervous system. Several animal inhalation studies have been conducted to assess the developmental toxicity of formaldehyde: The only exposure-related effect noted in these studies was decreased maternal body weight gain at the high-exposure level. No adverse effects on reproductive outcome of the fetuses that could be attributed to treatment were noted. An inhalation reference concentration (RfC), below which long-term exposures would not pose appreciable noncancer health risks, is not available for formaldehyde at this time.

iv. Acetaldehyde

Highway mobile sources contribute 29 percent of the national acetaldehyde emissions and HDVs are responsible for approximately 33 percent of the highway emissions.¹²⁴ Acetaldehyde is a saturated aldehyde that is found in vehicle exhaust and is formed as a result of incomplete combustion of both gasoline and diesel fuel. It is not a component of evaporative emissions. Acetaldehyde comprises 0.4 to 1.0 percent of total organic gas exhaust, depending on control technology and fuel composition.¹²⁵

The atmospheric chemistry of acetaldehyde is similar in many respects to that of formaldehyde.¹²⁶ Like formaldehyde, it is produced and destroyed by atmospheric chemical transformation. Mobile sources contribute to ambient acetaldehyde levels both by their primary emissions and by secondary formation resulting from their VOC emissions. Acetaldehyde emissions are classified as a probable human carcinogen. Studies in experimental animals provide sufficient evidence that long-term inhalation exposure to acetaldehyde causes an increase in the incidence of nasal squamous cell carcinomas (epithelial tissue) and adenocarcinomas (glandular tissue).ⁱⁱ ^{jj} The MLE estimate of a lifetime extra cancer risk from continuous acetaldehyde exposure is about $0.78 \times 10^{-6} / \mu\text{g}/\text{m}^3$. In other words, it is estimated that less than 1 person in one million exposed to $1 \mu\text{g}/\text{m}^3$ acetaldehyde continuously for their lifetime (70 years) would develop cancer as a result of their exposure. The agency is currently conducting a reassessment of risk from inhalation exposure to acetaldehyde.

ⁱⁱ Environmental Protection Agency, Health assessment document for acetaldehyde, Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office, Research Triangle Park, NC, EPA-600/8-86/015A (External Review Draft), 1987.

^{jj} Environmental Protection Agency, Integrated Risk Information System (IRIS), Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office, Cincinnati, OH, 1992.

Noncancer effects in studies with rats and mice showed acetaldehyde to be moderately toxic by the inhalation, oral, and intravenous routes.^{127 128 129} The primary acute effect of exposure to acetaldehyde vapors is irritation of the eyes, skin, and respiratory tract. At high concentrations, irritation and pulmonary effects can occur, which could facilitate the uptake of other contaminants. Little research exists that addresses the effects of inhalation of acetaldehyde on reproductive and developmental effects. The *in vitro* and *in vivo* studies provide evidence to suggest that acetaldehyde may be the causative factor in birth defects observed in fetal alcohol syndrome, though evidence is very limited linking these effects to inhalation exposure. Long-term exposures should be kept below the reference concentration of 9 µg/m³ to avoid appreciable risk of these noncancer health effects.¹³⁰

v. *Acrolein*

Highway mobile sources contribute 16 percent of the national acrolein emissions and HDVs are responsible for approximately 39 percent of these highway mobile source emissions. Acrolein is extremely toxic to humans from the inhalation route of exposure, with acute exposure resulting in upper respiratory tract irritation and congestion. The Agency developed a reference concentration for inhalation (RfC) of acrolein of 0.02 micrograms/m³ 1993. Although no information is available on its carcinogenic effects in humans, based on laboratory animal data, EPA considers acrolein a possible human carcinogen.¹³¹

vi. *Dioxins*

Recent studies have confirmed that dioxins are formed by and emitted from heavy-duty diesel trucks and are estimated to account for 1.2 percent of total dioxin emissions in 1995. In the environment, the pathway of immediate concern is the food pathway (e.g., human ingestion of certain foods, e.g. meat and dairy products contaminated by dioxin) which may be affected by deposition of dioxin from the atmosphere. EPA classified dioxins as probable human carcinogens in 1985. Recently EPA has proposed, and the Scientific Advisory Board has concurred, to classify one dioxin compound, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin as a human carcinogen and the complex mixtures of dioxin-like compounds as likely to be carcinogenic to humans using the draft 1996 carcinogen risk assessment guidelines.¹³² Using the 1986 cancer risk assessment guidelines, the hazard characterization for 2,3,7,8-tetrachlorodibenzo-*p*-dioxin is 'known' human carcinogen and the hazard characterization for complex mixtures of dioxin-like compounds is 'probable' human carcinogens. Acute and chronic noncancer effects have also been reported for dioxin.

b. Assessment of Exposure

This subsection describes the analysis conducted by the Agency to evaluate the impact of HDV standards on exposure to gaseous toxics present in significant quantities in heavy duty vehicle exhaust: benzene, formaldehyde, acetaldehyde, and 1,3-butadiene. The information in

this section is based on the 1999 ‘Analysis of the Impacts of Control Programs on Motor Vehicle Toxics Emissions and Exposure in Urban Areas and Nationwide’ (‘1999 Study’).¹³³

In these analyses, emissions of benzene, formaldehyde, acetaldehyde, and 1,3-butadiene were estimated using a toxic emission factor model, MOBTOX5b. This model is based on a modified version of MOBILE5b, which estimates emissions of regulated pollutants, and applies toxic fractions to total organic gas (TOG) estimates. The TOG basic emission rates used in this modeling incorporated the available elements for MOBILE6 used to develop the VOC inventory for this rule. The model accounted for differences in toxic fractions between technology groups, driving cycles, and normal versus high emitters. Impacts of fuel formulations were also addressed in the modeling.

We modeled toxic emissions for 10 urban areas and 16 geographic regions selected to encompass a broad range of I/M programs, fuel parameters, and temperature regimes. These urban areas and geographic regions are listed in Table II.A-24. The intent of the selection was to best characterize the different combinations of I/M programs, fuel parameters, and temperature regimes needed to perform accurate nationwide toxic emissions estimates. Every U.S. county in the country was then “mapped” to one of these modeled areas or regions (i.e., the emission factor for the modeled area was also used for the area “mapped” to it). Mapping was done based on a combination of geographic proximity, I/M program, and fuel control programs. Details of this process are provided in the 1999 Study. We then multiplied the resulting county level emission factors by county-level VMT estimates from EPA’s Emission Trends Database and summed the results across all counties to come up with nationwide emissions in tons.

Table II.A-24. Metropolitan Areas and Regions Included in Toxic Emissions Modeling

Chicago, IL	Atlanta, GA	Florida
Denver, CO	Western WA/ OR	Northeast States – non-I/M and non-RFG
Houston, TX	Northern CA	Northeast States - I/M and non-RFG
Minneapolis, MN	Southern CA	Northeast States - non-I/M and RFG
New York, NY	ID/ MT/ WY	Ohio Valley – non-I/M and non-RFG
Philadelphia, PA	UT/ NM/NV	Ohio Valley – I/M and non-RFG
Phoenix, AZ	West TX	Ohio Valley – I/M and RFG
Spokane, WA	ND/ SD/ NB/ IA/ KS/ Western MO	Northern MI/ WI
St. Louis, MO	AR/ MS/ AL/ SC/ Northern LA	

Modeling for these areas was accomplished on a seasonal basis. Information on fuel properties for 1990 and 1996 was obtained from surveys conducted by the National Institute for Petroleum and Energy Research (NIPER) and the American Automobile Manufacturers Association (AAMA). Fuel parameters for 2007 and 2020 were projected from 1996 baseline values using information from a February 26, 1999 report from Mathpro to the American Petroleum Institute.¹³⁴ Data from the EPA Emission Trends Database and other agency sources were used to develop appropriate local modeling parameters for I/M programs, Stage II refueling controls, fuel RVP, average ambient temperature, and other inputs.

These emissions data were used as input to the HAPEM-MS3 exposure model to assess ambient exposures to the four gaseous toxics discussed in this section. With the 1990 CO exposure estimates generated by the HAPEM-MS3 model for each urban area, EPA determined the fraction of exposure that was a result of on-road motor vehicle emissions. This calculation was accomplished by scaling the exposure estimates (which reflect exposure to total ambient CO) by the fraction of the 1990 CO emissions inventory from on-road motor vehicles, determined from the EPA Emission Trends database.^{135 136} Nationwide urban CO exposure from on-road motor vehicles was estimated by first calculating a population-weighted average CO exposure for the ten modeled areas. This number was adjusted by applying a ratio of population-weighted annual average CO for urban areas in the entire country versus average ambient CO concentration for the modeled areas. To estimate rural exposure, the urban estimate was scaled downward using estimates of urban versus rural exposure from the 1993 *Motor Vehicle-Related Air Toxics Study*.¹³⁷

Modeled on-road CO exposure for 1990 was divided by 1990 CO grams per mile emission estimates to create a conversion factor. The conversion factor was applied to modeled toxic emission estimates (in grams per mile terms) to determine exposure to on-road toxic emissions, as shown in Equation 2:

$$\text{TOX}_{\text{Exposure}(\mu\text{g}/\text{m}^3)} = [\text{CO}_{\text{Exposure}(\mu\text{g}/\text{m}^3)} / \text{CO}_{\text{EF}(\text{g}/\text{mi})}]_{1990} \times \text{TOX}_{\text{EF}(\text{g}/\text{mi})} \quad (2)$$

where TOX reflects one of the four toxic pollutants considered in this study.

The ambient exposure estimates for calendar years 1996, 2007, and 2020 were adjusted for VMT growth relative to 1990. Exposure estimates were adjusted to account for the VOC emissions modeling conducted for this rulemaking.

To account for atmospheric loss of 1,3-butadiene that varies seasonally^{kk}, exposure estimates were adjusted using the following multiplicative factors: 0.44 for summer, 0.70 for spring and fall, and 0.96 for winter.¹³⁸ These factors account for the difference in reactivity

^{kk} Seasons were defined as Spring (March, April, May); Summer (June, July, August); Fall (September, October, November); Winter (December, January, February).

between relatively inert CO, which is being used as the tracer for toxics exposure, and 1,3-butadiene. In contrast, estimated exposure to formaldehyde and acetaldehyde was based on direct emissions. For these pollutants, removal of direct emissions in the afternoon was assumed to be offset by secondary formation. We evaluated the validity of this assumption by comparing our results to draft average ambient concentration estimates from the 1996 National Air Toxics Assessment (NATA). The NATA for 1996 used the same inventory applied to the analysis presented here for motor vehicle toxics. The Assessment System for Population Exposure Nationwide (ASPEN) dispersion model was used in the NATA to estimate ambient concentrations of several mobile source toxics, including aldehydes. Assumptions applied in the ASPEN model include an estimate that 68 percent of formaldehyde is primary emissions (i.e. direct emission as opposed to secondary formation in the atmosphere), while only about 20 percent of acetaldehyde is assumed to be primary emissions. The comparison between ASPEN concentrations and HAPEM-MS3 exposures indicated fairly good agreement for formaldehyde, but suggested the HAPEM-MS3 exposure estimates for acetaldehyde may be low by a factor of three. Thus, our acetaldehyde exposure estimates were adjusted upward by a factor of three to match draft ambient concentration estimates from the National Air Toxics Assessment.

HAPEM-MS3 does not account for exposures originating within microenvironments. For instance, the model would not account for exposure to evaporative benzene emissions indoors from vehicles parked in attached garages, or to vehicles during refueling.

Table II.A-25 presents annual average nationwide exposure estimates from all highway motor vehicles for benzene, acetaldehyde, formaldehyde and 1,3-butadiene. The projected contribution of HDVs to the highway motor vehicle exposures estimates in 2007 is 13 percent for benzene, 51 percent for acetaldehyde, 59 percent for formaldehyde, and 9 percent for 1,3-butadiene. With today's standards in place, exposure to toxics from all HDVs in 2020 would be reduced by 7 percent for benzene, 20 percent for acetaldehyde, 23 percent for formaldehyde, and 7 percent for 1,3-butadiene. And exposure to toxics from all highway sources in 2020 (Table II.A-25) would be reduced by 2 percent for benzene, 15 percent for acetaldehyde, 18 percent for formaldehyde, and 5 percent for 1,3-butadiene.

Table II.A-25. Modeled Average 50-State Ambient Exposure to Gaseous Toxics from All Highway Motor Vehicles ($\mu\text{g}/\text{m}^3$) in 1990, 1996, 2007, and 2020 without 2007 HDV Standards and for 2020 with 2007 HDV Standards

<i>Toxic</i>	<i>1990</i>	<i>1996</i>	<i>2007</i>	<i>2020</i>	<i>2020^A</i>	<i>Percent Reduction in 2020 with 2007 HDV Standards^B</i>
Benzene	1.07	0.71	0.38	0.28	0.28	2%
Acetaldehyde	0.51	0.38	0.21	0.22	0.18	15%
Formaldehyde	0.57	0.37	0.18	0.17	0.14	18%
1,3-Butadiene	0.11	0.08	0.03	0.03	0.03	5%

^A Exposure estimates with the 2007 Heavy-Duty Vehicle Standards.

^B Percent reductions use exposures calculated to four decimal places.

Separately, exposure estimates were also generated for the 10 urban areas listed in Table II.A-24. In Denver, CO, Minneapolis, MN, Spokane, WA, Atlanta, GA and Phoenix, AZ, exposure to these four gaseous toxic compounds resulting from HDV emissions is projected to be higher than the national average in 2007. Of the cities modeled, Denver, and Phoenix are projected to have two-fold higher exposure estimates for acetaldehyde, formaldehyde and 1,3-butadiene from HDVs compared with the national average in 2007.

6. Visibility/Regional Haze

Visibility impairment is the haze that obscures what we see, and is caused by the presence of tiny particles in the air. These particles cause light to be scattered or absorbed, thereby reducing visibility. Visibility impairment, also called regional haze, is a complex problem that relates to natural conditions and also several pollutants. Visibility in our national parks and monuments, and many urban areas of the country, continues to be obscured by regional and local haze.

The principle cause of visibility impairment is fine particles, primarily sulfates, but also nitrates, organics, and elemental carbon and crustal matter. Particles between 0.1 and one micrometers in size are most effective at scattering light, in addition to being of greatest concern for human health. Of the pollutant gases, only NO_2 absorbs significant amounts of light; it is partly responsible for the brownish cast of polluted skies. However, it is responsible for less than ten percent of visibility reduction.

In the eastern U.S., reduced visibility is mainly attributable to secondary particles, particularly those less than a few micrometers in diameter. Based on data collected by the Interagency Monitoring of Protected Visual Environments (IMPROVE) network for visibility monitoring, sulfate particles account for about 50-70 percent of annual average light extinction in eastern locations. Sulfate plays a particularly significant role in the humid summer months, most notably in the Appalachian, northeast, and mid-south regions. Nitrates, organic carbon, and elemental carbon each account for between 10–15 percent of total light extinction in most eastern locations. Rural areas in the eastern U.S. generally have higher levels of impairment than most remote sites in the western U.S., generally due to the eastern U.S.'s higher levels of man-made pollution, higher estimated background levels of fine particles, and higher average relative humidity levels.

The relative contribution of individual pollutants to visibility impairment vary geographically. While secondary particles still dominate in the West, direct particulate emissions from sources such as woodsmoke contribute a larger percentage of the total particulate load than in the East. In the rural western U.S., sulfates also play a significant role, accounting for about 25–40 percent of estimated total light extinction in most regions. In some areas, such as the Cascades region of Oregon, sulfates are estimated to account for over 50 percent of annual average light extinction. Organic carbon typically is estimated to be responsible for 15–35 percent of total light extinction in the rural western U.S. and elemental carbon (absorption) accounts for about 15–25 percent, so the total carbonaceous contribution is between 30 and 60 percent. Soil dust (coarse PM) accounts for about 10–20 percent. Nitrates typically account for less than 10 percent of visibility impairment.¹³⁹

The CAA requires EPA to address visibility impairment, or visual air quality, through a number of programs. These programs include the national visibility program under sections 169a and 169b of the Act, the Prevention of Significant Deterioration program for the review of potential impacts from new and modified sources, and the secondary NAAQS for PM₁₀ and PM_{2.5}. The national visibility program established in 1980 requires the protection of visibility in 156 mandatory Federal Class I areas across the country (primarily national parks and wilderness areas). The CAA established as a national visibility goal, “the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Federal class I areas in which impairment results from manmade air pollution.” The Act also calls for State programs to make “reasonable progress” toward the national goal. In July 1999, EPA promulgated a program to address regional haze in the nation’s national parks and wilderness areas (see 64 FR 35714, July 1, 1999).

Since mobile sources contribute to visibility-reducing PM, control programs that reduce the mobile source emissions of direct and indirect PM would have the effect of improving visibility. Western Governors, in commenting on the Regional Haze Rule and on protecting the 16 Class I areas on the Colorado Plateau, stated that, “...the federal government must do its part in regulating emissions from mobile sources that contribute to regional haze in these areas...” and called on EPA to make a “binding commitment to fully consider the Commission’s

recommendations related to the ... federal national mobile source emissions control strategies”, including Tier 2 vehicle emissions standards.¹⁴⁰ The Grand Canyon Visibility Transport Commission’s report found that reducing total mobile source emissions is an essential part of any program to protect visibility in the Western U.S.¹⁴¹ The Commission identifies mobile source pollutants of concern as VOC, NO_x, and elemental and organic carbon.

Visibility is greatly affected by ambient PM_{2.5} concentration, with PM_{2.5} concentrations below the NAAQS being sufficient to impair visibility. Black elemental carbon particles are a dominant light adsorbing species in the atmosphere¹⁴², and a major component of diesel exhaust. The reductions in ambient PM_{2.5} from the standards in this rulemaking are expected to contribute to visibility improvements across the U.S. The geographical pattern of the improvement mirrors that of the PM_{2.5} reductions. Visibility improvements have value to Americans in both recreational areas traditionally known for scenic vistas, and in the urban areas where people spend most of their time.

7. Acid Deposition

Acid deposition, or acid rain as it is commonly known, occurs when SO₂ and NO_x react in the atmosphere with water, oxygen, and oxidants to form various acidic compounds that later fall to earth in the form of precipitation or dry deposition of acidic particles.¹¹ It contributes to damage of trees at high elevations and in extreme cases may cause lakes and streams to become so acidic that they cannot support aquatic life. In addition, acid deposition accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. To reduce damage to automotive paint caused by acid rain and acidic dry deposition, some manufacturers use acid-resistant paints, at an average cost of \$5 per vehicle--a total of \$61 million per year if applied to all new cars and trucks sold in the U.S.

Acid deposition primarily affects bodies of water that rest atop soil with a limited ability to neutralize acidic compounds. The National Surface Water Survey (NSWS) investigated the effects of acidic deposition in over 1,000 lakes larger than 10 acres and in thousands of miles of streams. It found that acid deposition was the primary cause of acidity in 75 percent of the acidic lakes and about 50 percent of the acidic streams, and that the areas most sensitive to acid rain were the Adirondacks, the mid-Appalachian highlands, the upper Midwest and the high elevation West. The NSWS found that approximately 580 streams in the Mid-Atlantic Coastal Plain are acidic primarily due to acidic deposition. Hundreds of the lakes in the Adirondacks surveyed in the NSWS have acidity levels incompatible with the survival of sensitive fish species. Many of the over 1,350 acidic streams in the Mid-Atlantic Highlands (mid-Appalachia) region have already experienced trout losses due to increased stream acidity. Emissions from U.S. sources

¹¹ Much of the information in this subsection was excerpted from the EPA document, *Human Health Benefits from Sulfate Reduction*, written under Title IV of the 1990 Clean Air Act Amendments, U.S. EPA, Office of Air and Radiation, Acid Rain Division, Washington, DC 20460, November 1995.

contribute to acidic deposition in eastern Canada, where the Canadian government has estimated that 14,000 lakes are acidic. Acid deposition also has been implicated in contributing to degradation of high-elevation spruce forests that populate the ridges of the Appalachian Mountains from Maine to Georgia. This area includes national parks such as the Shenandoah and Great Smoky Mountain National Parks.

The SO_x and NO_x reductions from today's rule would help reduce acid rain and acid deposition, thereby helping to reduce acidity levels in lakes and streams throughout the country and help accelerate the recovery of acidified lakes and streams and the revival of ecosystems adversely affected by acid deposition. Reduced acid deposition levels would also help reduce stress on forests, thereby accelerating reforestation efforts and improving timber production. Further deterioration of our historic buildings and monuments, and of buildings, vehicles, and other structures exposed to acid rain and dry acid deposition also would be slowed, and the costs borne to prevent acid-related damage may also decline. While the reduction in sulfur and nitrogen acid deposition would be roughly proportional to the reduction in SO_x and NO_x emissions, respectively, the precise impact of today's rule would differ across different areas.

8. Eutrophication and Nitrification

Nitrogen deposition into bodies of water can cause problems beyond those associated with acid rain. The Ecological Society of America has included discussion of the contribution of air emissions to increasing nitrogen levels in surface waters in a recent major review of causes and consequences of human alteration of the global nitrogen cycle in its *Issues in Ecology* series.^{mm} Long-term monitoring in the United States, Europe, and other developed regions of the world shows a substantial rise of nitrogen levels in surface waters, which are highly correlated with human-generated inputs of nitrogen to their watersheds. These nitrogen inputs are dominated by fertilizers and atmospheric deposition.

Human activity can increase the flow of nutrients into those waters and result in excess algae and plant growth. This increased growth can cause numerous adverse ecological effects and economic impacts, including nuisance algal blooms, dieback of underwater plants due to reduced light penetration, and toxic plankton blooms. Algal and plankton blooms can also reduce the level of dissolved oxygen, which can also adversely affect fish and shellfish populations. This problem is of particular concern in coastal areas with poor or stratified circulation patterns, such as the Chesapeake Bay, Long Island Sound, or the Gulf of Mexico. In such areas, the "overproduced" algae tends to sink to the bottom and decay, using all or most of the available oxygen and thereby reducing or eliminating populations of bottom-feeder fish and

^{mm} Vitousek, Peter M., John Aber, Robert W. Howarth, Gene E. Likens, et al. 1997. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences. *Issues in Ecology*. Published by Ecological Society of America, Number 1, Spring 1997.

shellfish, distorting the normal population balance between different aquatic organisms, and in extreme cases causing dramatic fish kills.

Collectively, these effects are referred to as eutrophication, which the National Research Council recently identified as the most serious pollution problem facing the estuarine waters of the United States (NRC, 1993). Nitrogen is the primary cause of eutrophication in most coastal waters and estuaries.^{mm} On the New England coast, for example, the number of red and browntides and shellfish problems from nuisance and toxic plankton blooms have increased over the past two decades, a development thought to be linked to increased nitrogen loadings in coastal waters. We believe that airborne NO_x contributes from 12 to 44 percent of the total nitrogen loadings to United States coastal water bodies. For example, some estimates assert that approximately one-quarter of the nitrogen in the Chesapeake Bay comes from atmospheric deposition.

Excessive fertilization with nitrogen-containing compounds can also affect terrestrial ecosystems.^{oo} Research suggests that nitrogen fertilization can alter growth patterns and change the balance of species in an ecosystem, providing beneficial nutrients to plant growth in areas that do not suffer from nitrogen over-saturation. In extreme cases, this process can result in nitrogen saturation when additions of nitrogen to soil over time exceed the capacity of the plants and microorganisms to utilize and retain the nitrogen. This phenomenon has already occurred in some areas of the U.S.

Deposition of nitrogen from heavy-duty vehicles contributes to these effects. In the Chesapeake Bay region, modeling shows that mobile source deposition occurs in relatively close proximity to highways, such as the I-95 corridor which covers part of the Bay surface. The NO_x reductions from the standards for heavy-duty vehicles should reduce the eutrophication problems associated with atmospheric deposition of nitrogen into watersheds and onto bodies of water, particularly in aquatic systems where atmospheric deposition of nitrogen represents a significant portion of total nitrogen loadings.

^{mm} Much of this information was taken from the following EPA document: *Deposition of Air Pollutants to the Great Waters-Second Report to Congress*, Office of Air Quality Planning and Standards, June 1997, EPA-453/R-97-011.

^{oo} Terrestrial nitrogen deposition can act as a fertilizer. In some agricultural areas, this effect can be beneficial.

9. POM Deposition

EPA's Great Waters Program has identified 15 pollutants whose deposition to water bodies has contributed to the overall contamination loadings to these Great Waters.^{pp} One of these 15 compounds, a group known as polycyclic organic matter (POM), are compounds that are mainly adhered to the particles emitted by mobile sources and later fall to earth in the form of precipitation or dry deposition of particles. The mobile source contribution of the 7 most toxic POM is at least 62 tons/year^{qq} and represents only those POM that are adhered to mobile source particulate emissions. The majority of these emissions are produced by diesel engines.

POM is generally defined as a large class of chemicals consisting of organic compounds having multiple benzene rings and a boiling point greater than 100°C. Polycyclic aromatic hydrocarbons are a chemical class that is a subset of POM. POM are naturally occurring substances that are byproducts of the incomplete combustion of fossil fuels and plant and animal biomass (e.g., forest fires). Also, they occur as byproducts from steel and coke productions and waste incineration.

Evidence for potential human health effects associated with POM comes from studies in animals (fish, amphibians, rats) and in human cells culture assays. Reproductive, developmental, immunological, and endocrine (hormone) effects have been documented in these systems. Many of the compounds included in the class of compounds known as POM are classified by EPA as probable human carcinogens based on animal data.

The particulate reductions from today's rule would help reduce not only the particulate emissions from highway diesel engines but also the deposition of the POM adhered to the particles, thereby helping to reduce health effects of POM in lakes and streams, accelerate the recovery of affected lakes and streams, and revive the ecosystems adversely affected.

10. Carbon Monoxide

We believe that the aftertreatment technology that would be used to meet the standards for NO_x, and diesel particles would result in a per-vehicle reduction in excess of 90 percent in CO from baseline levels. As of December 1999, there were 17 CO nonattainment areas with a population of about 30 million people.¹⁴³ An additional 24 areas with a combined population of 22 million are designated as CO maintenance areas. The broad trends indicate that ambient levels of CO are declining. The standards being promulgated today would help reduce levels of carbon monoxide (CO).

^{pp} Much of this information was taken from the following EPA document: *Deposition of Air Pollutants to the Great Waters-Second Report to Congress*, Office of Air Quality Planning and Standards, June 1997, EPA-453/R-97-011. You are referred to that document for a more detailed discussion.

^{qq} *The 1996 National Toxics Inventory*, Office of Air Quality Planning and Standards, October 1999.

B. Heavy-Duty Diesel Inventory Impacts

This part of the environmental impact chapter presents the emission inventory reductions we anticipate from heavy-duty vehicles as a result of our NMHC, NO_x, and PM emission standards and as a result of our fuel sulfur standards. This section provides detail on our emissions inventory calculations and catalogs changes from the NPRM analysis. In addition, this section contains a sensitivity analysis of deterioration, tampering, and malmaintenance on PM emissions.

1. Description of Calculation Method

We calculated our emissions reductions by first determining baseline emissions from HDVs then determining the percent reduction by calendar year. The determination of the baseline and controlled inventories is described below.

For the controlled emission inventory, we actually present two cases. These two control cases are labeled as *Air Quality Analysis Case* and *Updated Control Case*. The *Air Quality Analysis Case* is used in the county-by-county, hour-by-hour air quality analyses associated with this rule. This inventory was developed using the assumptions and proposed standards presented in the NPRM for this rule. Because the detailed air quality analyses take several months to perform, we had to begin as soon as the NPRM was finalized and were not able to incorporate any changes in the final standards.

The *Updated Control Case* incorporates changes in the standards and assumptions from the NPRM to the FRM. Although the differences are fairly small, the *Updated Control Case* more precisely represents the reductions associated with the final standards and is used in our cost-effectiveness analysis. These updates only affect the control inventory and do not affect the baseline inventory.

a. Baseline Emissions Inventory

i. HC, NO_x, CO, PM, and SO_x

In modeling emissions from heavy-duty diesel engines, our intent is to be consistent with the upcoming MOBILE6 model. MOBILE6 is the upcoming version of the MOBILE model that we historically use to develop calendar year specific emission factors for highway vehicles. This model will be publically available in early 2001. However, the new data used develop this model has been made publicly available for stakeholder review. Therefore, we use new published data that was developed for use in the upcoming MOBILE6.

Emissions inventories from HDVs were calculated at the county level for 1996, 2007, 2020, and 2030. MOBILE5 was used to calculate VOC,^r NO_x, and CO emissions inventories; PART5 was used to calculate PM and SO_x. Adjustment factors were then applied to account for the new data collected as part of the development of the upcoming MOBILE6 emission factor model. This methodology is described and detailed inventories are presented in the docket.^{144 145} The adjustment factors used to incorporate the new data and the development of these adjustment factors are also described in the docket.^{146 147} No adjustments were made to the brake and tire wear calculations.

ii. *Fuel Consumption*

To determine the impact of the low sulfur diesel fuel requirement on vehicle operation costs and on emissions, we first need to calculate the diesel fuel consumption. We calculated HDDE fuel consumption using Equation 1:

$$Gallons_{CY} = j_{class} \{ VMT \times j_{MY/age} [FC \times TF_{age}] \} \quad (1)$$

where:

Gallons_{CY} - fuel consumption in gallons/year

class - LHDDE, MHDDE, HHDDE, and urban bus

VMT- total vehicle miles traveled in a given calendar year by class

MY/age - distribution of vehicles in a calendar year by vehicle age

FC - fuel consumption in gallons per mile

TF_{age} - travel fraction of vehicles from each model year in a given calendar year

VMT projections are described in the same report as the calculations of VOC, NO_x, CO, PM, and SO_x.¹⁴⁸ The travel fraction is described in the memo which details the adjustment factors.¹⁴⁹

Historical fuel consumption estimates (1987-1996) come from a report performed to support the upcoming MOBILE6 model.¹⁵⁰ These historical fuel consumption estimates suggest that fuel economy is improving. For future fuel consumption estimates, we extrapolate the historical estimates into the future using a constant, linear improvement in terms of miles per gallon. We use a single, weighted average, growth rate for MHDDEs and HHDDEs. This is because a straight projection of the MHDDE and HHDDE fuel economies would suggest that HHDDEs would have better fuel economy than MHDDEs beginning in 2020. We don't believe this is likely because of the lower weight of MHDDEs. Table II.B-3 presents per-vehicle the HDDE fuel economy estimates for selected years.

^r Volatile Organic Compounds—This includes exhaust and evaporative hydrocarbon emissions.

Table II.B-1. HDDE Fuel Economy Estimates by Model Year (miles per gallon)

<i>Model Year</i>	<i>LHDDE</i>	<i>MHDDE</i>	<i>HHDDE</i>	<i>Urban Bus</i>
1990	10.7	7.7	5.9	3.6
2000	11.8	8.1	6.6	4.0
2010	12.9	8.7	7.3	4.4
2020	14.0	9.4	7.9	4.8

To fully evaluate the effects of the fuel sulfur level standards, we also need to consider other sources that will likely consume low sulfur fuel produced for HDDEs. These sources include light-duty vehicles, off-highway engines, and stationary sources. We refer to the low sulfur fuel used in sources other than highway engines as spillover.

To include the gallons consumed by light-duty diesel vehicles, we use estimates developed for our Tier 2 final rule¹⁵¹ and fuel economy estimates of 25 mpg and 16.7 mpg for light-duty diesel vehicles (LDDV) and light-duty diesel trucks (LDDT), respectively.¹⁵² We divided the VMT values within each of these light-duty diesel fuel categories by the corresponding MOBILE6 projected fuel economy estimates to derive the diesel fuel consumption for each category per year.

Highway engines are not the only sources that burn highway diesel fuel. Due to limitations of the fuel production and distribution system, a considerable amount of low sulfur diesel fuel is currently consumed in off-highway and other applications. To estimate the amount of highway diesel fuel consumed by other sources, we used data compiled by the Energy Information Administration (EIA) which showed that combined 1996 production plus importation minus exportation of highway diesel fuel was 32.8 billion gallons.¹⁵³ We then subtracted our estimates of HDDE and LDV diesel fuel consumption to determine the spillover to sources other than highway engines.

For future years we estimate that spillover will increase as fuel production increases. We recognize that spillover could decrease in future years if the highway fuel cost were to increase significantly with respect to the off-highway fuel cost and if the fuel were redistributed economically. However, we believe the proportion of spillover is largely driven by the limitations of the fuel distribution system and that it is not likely to change substantially in response to this rule.

iii. Crankcase Emissions

We anticipate some benefits in NMHC, NO_x, and PM from the closed crankcase requirements for turbocharged HDDEs. Based on limited engine testing, we estimate that crankcase emissions of NMHC and PM from HDDEs are each about 0.01 g/bhp-hr.¹⁵⁴ NO_x data varies, but crankcase NO_x emissions may be as high as NMHC and PM. Therefore, we use the same crankcase emission factor of 0.01 g/bhp-hr for each of the three constituents.

iv. Air Toxics

We use baseline gaseous toxic emission estimates for heavy duty gasoline vehicles prepared by Sierra Research. Sierra developed inventory estimates for several gaseous mobile source air toxics (MSAT), including acetaldehyde, benzene, 1-3 butadiene, and formaldehyde.¹⁵⁵ The Sierra study provided estimates of toxic emissions under various control scenarios for several years. These specific MSATs were addressed because detailed information on the emission impacts of emission control technologies, fuel properties, and other parameters were available for these compounds.

The emissions of benzene, formaldehyde, acetaldehyde, and 1,3-butadiene were estimated using a toxic emission factor model, MOBTOX5b. This model is based on a modified version of MOBILE5b, which estimates emissions of regulated pollutants, and essentially applies toxic fractions to total organic gas (TOG) estimates. The TOG basic emission rates used in this modeling incorporated available elements from MOBILE6 used to develop the VOC inventory for the Tier 2 final rule. The model accounted for differences in toxic fractions between technology groups, driving cycles, and normal versus high emitting vehicles and engines (“high emitters”). Impacts of fuel formulations were also addressed in the modeling.

Sierra modeled toxic emissions for 10 urban areas and 16 geographic regions. The areas were selected to encompass a broad range of I/M programs, fuel parameters, and temperature regimes. The intent of the selection process was to best characterize the different combinations needed to perform accurate nationwide toxic emissions estimates. Every U. S. county in the country was then “mapped” to one of these modeled areas or regions (i.e., the emission factor for the modeled area was also used for the area “mapped” to it). Mapping was done based on a combination of geographic proximity, I/M program, and fuel control programs.

Modeling for these areas was done on a seasonal basis. Information on fuel properties for was obtained from surveys conducted by the National Institute for Petroleum and Energy Research (NIPER) and the American Automobile Manufacturers Association (AAMA) and additional information from the American Petroleum Institute. Data from the EPA Emission Trends Database and other agency sources were used to develop appropriate local modeling parameters for I/M programs, Stage II refueling controls, fuel RVP, average ambient temperature, and other inputs.

To estimate the effect of the 2007 and later model year heavy-duty engine standards on toxics inventories, we started with the toxics inventories estimated in the Sierra study assuming

all heavy-duty engine programs up until the 2004 model year standards are in effect. Using these “baseline” inventory estimates for 2007 and 2020 and the nationwide vehicle miles traveled estimates from the same study, we then estimated the “baseline” gram per mile emissions for the five toxics (on a nationwide, average basis) for 1996, 2007 and 2020. The emission factors for other years, were interpolated from these estimates.

Finally, we then multiplied the gram per mile estimates by the nationwide vehicle mile traveled estimates developed for this rule, to obtain the heavy-duty gasoline and diesel vehicle toxic inventories used in this analysis. Because benzene has an exhaust and an evaporative component, we applied the percent reduction based on total (exhaust and evaporative) NMHC benefits. For formaldehyde, acetaldehyde, and 1,3-butadiene, which do not have an evaporative component, we applied the percent reduction based on exhaust NMHC only.

b. Controlled Emissions Inventory (Air Quality Analysis Case)

i. HC, NO_x, CO, PM, and SO_x

To determine the emissions reductions in NMHC, NO_x, CO, and PM we look at the percent emission reductions expected from new engines then calculate percent reductions by calendar year using the travel fractions discussed above. For the *Air Quality Analysis Case* we base the calculations on the proposed HDV standards. This methodology is described and detailed inventories are presented in the docket.^{156 157} We assume that manufacturers will design their engine with a compliance margin below the standards. Based on historical certification data, we use an eight percent compliance margin for HDDEs and a 25 percent compliance margin for HDGVs.

Based on our analysis of the aftertreatment technology described in Chapter III, HDDEs meeting the standards should have very low levels of CO. Although the standards give manufacturers the same phase-in for NMHC as for NO_x, we model the NMHC reductions to be fully in place for diesel engines in 2007. We believe the use of aftertreatment for PM control will result in HDDEs meeting the NMHC standards in 2007 and will result in 90 percent reductions in CO levels soon as the PM standard goes into effect in 2007. In the *Air Quality Analysis Case*, we assume that particulate traps will result in a 90 percent reduction in NMHC; however, as discussed later, we changed this assumption in the *Updated Control Case*.

We assume that hot soak, diurnal and resting loss emissions from HDGVs would be reduced proportionally to the reduction in the evaporative emission standard. However, we only apply these reductions to the emissions of HDGVs which pass the EPA pressure and EPA purge functional test procedures. We do not claim any benefits from HDGVs which fail these tests.

The majority of the projected PM reductions from HDDEs are directly a result of the PM standard. However, some PM reductions will come from reducing sulfur in the fuel. Reducing sulfur in the fuel decreases the amount of direct sulfate PM (DSPM) emitted from heavy-duty

diesel engines and other engines using highway fuel. This section describes the calculations exhaust emission PM benefits that are directly the result of the 2007 standards. DSPM benefits from the existing fleet are calculated separately and are discussed later. For SO_x reductions, we look at the reduction of sulfur in the fuel and the amount of sulfur in the fuel that can be assumed to be converted to SO₂.

The control emission factors and percent reductions by calendar year are described in more detail in the docket.^{158 159}

ii. *Direct Sulfate PM*

Once the low sulfur diesel fuel requirements go into effect, pre-2007 model year HDDEs will be using low sulfur fuel, as will engines using new PM control technology. Because these pre-2007 engines will be certified with high sulfur fuel, they will achieve reductions in PM beyond their certification levels.

For engines built prior to 2007 that use low sulfur fuel in 2007 and later, we need to calculate the PM benefit associated with the reduction of direct sulfate PM. Equation 2 shows how we calculate this benefit and express it in terms of an emission factor. We did not consider deterioration for DSPM which is consistent with our analysis of total PM. We must calculate the per-vehicle average g/mi reduction independently for each class and calendar year.

$$DSPM_{TONS} = 10^{-6} \times ppmS \times MWR \times S_{conv} \times FF \times FC \times density/2000 \quad (2)$$

where:

DSPM_{TONS} - direct sulfate PM for a given calendar year [short tons]
 ppmS = average fuel sulfur level expressed in parts per million
 MWR - molecular weight ratio of DSPM measured on a filter to sulfur in the fuel
 = 224/32 (224 is the molecular weight of H₂SO₄ hydrated seven times)
 S_{conv} - % of sulfur in fuel converted to direct sulfate PM
 FF - fraction of VMT from pre-2007 MY fleet
 FC - total consumption of fuel intended for HDDEs in gallons
 density - fuel density = 7.1 lbs/gallon

For the reduction in average fuel sulfur level, we use 334 ppm. We base this reduction on an average baseline fuel level of 340 ppm S and an average low sulfur fuel level of 7 ppm S with adjustments for sulfur in the oil. We estimate that oil adds the equivalent of about 1 ppm S to the fuel. In the baseline case most of the crankcase vapor is vented to the atmosphere which minimizes the oil burned in the cylinder. In the control case where there are closed crankcase requirements, we consider the oil recovery system discussed in Chapter III.

We use the fuel consumption estimates described above in Section B.1.a.iv. This fuel consumption includes highway fuel burned in heavy-duty engines, light-duty vehicles, and other sources which use distillate fuel.

For engines not using aftertreatment, we assume that 2 percent of the sulfur in the fuel is converted to direct sulfate PM. This conversion rate is consistent with the PART5 emission model. We model the use of low sulfur fuel to begin in mid-2006.

iii. Crankcase Emissions

By routing crankcase vapors to the exhaust upstream of the aftertreatment systems, HDDE manufacturers should be able to reduce crankcase emissions by about the same percentage as for engine-out exhaust. For this analysis, we recognize that the crankcase emissions will be included in the total exhaust emissions when the engine is designed to the standards. Because exhaust emissions would have to be reduced slightly to offset any crankcase emissions, the crankcase emission control is functionally equivalent to a 100 percent reduction in crankcase emissions.

The engine data we use to determine crankcase emission levels is based on new HDDEs. We do not have data on the effect of in-use deterioration of crankcase emissions. However, we expect that these emissions would increase as the engine wears. Therefore, this analysis may underestimate the benefits that would result from our crankcase emission requirements.

iv. Air Toxics

We use the same methodology to calculate the controlled toxics inventory as the baseline inventory. We lack data on how the toxic fractions of the hydrocarbons may change for engines designed to meet the new standards; therefore, we assume for the sake of analysis that the toxic fractions do not change. In other words, we assume the same percent reductions in air toxics as we calculate for hydrocarbons.

c. Controlled Emissions Inventory (Updated Control Case)

The main purpose of the updated control case is to consider changes between the standards proposed in the NPRM and the standards finalized today. For these calculations, we consider the heavy-duty vehicle standards as presented in Table II.B-1 and the standards phase-in dates presented in Table II.B-2. All HDDEs are engine-certified, however; most heavy-duty gasoline vehicles are chassis-certified. We refer to gasoline engines sold as part of a chassis as “completes” and require these engines to be certified on a chassis-based test provided that the vehicle does not have a gross vehicle weight rating more than 14,000 pounds. Other gasoline engines are tested on an engine dynamometer and we refer to these as “incompletes.”

Table II.B-2. Heavy-Duty Vehicle Exhaust Emissions Standards

<i>Class</i>	<i>Units</i>	<i>NMHC</i>	<i>NO_x</i>	<i>PM</i>
HDDE	g/bhp-hr	0.14	0.20	0.01
HDGV, 2b Completes	g/mile	0.195	0.2	0.02
HDGV, 3 Completes	g/mile	0.230	0.4	0.02
HDGV Incompletes	g/bhp-hr	0.14	0.20	0.01

Table II.B-3. Heavy-Duty Vehicle Standards Phase-In (percent of production)

<i>Model Year</i>	<i>HDDE (NMHC & NO_x)</i>		<i>HDDE (PM)^A</i>		<i>HDGV^B</i>	
	<i>NPRM</i>	<i>FRM</i>	<i>NPRM</i>	<i>FRM</i>	<i>NPRM</i>	<i>FRM</i>
2007	25%	50%	100%	100%	100%	0%
2008	50%	50%	100%	100%	100%	50%
2009	75%	50%	100%	100%	100%	100%
2010+	100%	100%	100%	100%	100%	100%

^A This applies to the closed crankcase requirement as well.

^B This applies to evaporative emission standards as well.

As shown above, the actual values of the standards have not changed since proposal. However, the implementation dates have changed somewhat. One other change is that we assume that diesel engine manufacturers will design their engines to meet the NMHC with a small compliance margin. In the NPRM, we assumed that particulate traps would result in a 90 percent reduction in NMHC. This is discussed in more detail in Chapter III. Other than for NMHC, the net effect of the changes in the FRM from the NPRM for HDDEs is small. However, the FRM implementation dates essentially delay the HDGV standards by a year and a half. The *Updated Control Case* calculates the reductions from HDVs using the same methodology as the *Air Quality Analysis Case* except that the new HDDE NMHC assumptions and FRM implementation dates are used.

Also, we consider the low sulfur diesel temporary compliance flexibilities and hardship provisions in our calculations. These provisions allow as little as 75 percent of highway diesel fuel sales to be 15 ppm sulfur beginning in 2006; increasing to 100% in 2010. In the NPRM, we

proposed to require that all highway diesel fuel meet the standard in 2006. This delay in production affects SO_x and DSPM benefits from HDDEs.

2. HDDE Emission Reductions

a. Anticipated Reductions due to the New HDDE Standards

This section looks at tons/year emission inventories of NO_x, PM, and NMHC from HDDEs. These are the emissions that we are directly regulating from HDDEs. We present our projected baseline and controlled emissions inventories in addition to our anticipated benefits. Where there is a difference, we present both the results from the *Air Quality Analysis Case* (AQAC) and the *Updated Control Case* (Updated). In addition, this section presents the total production of highway diesel fuel which will be required to meet the low sulfur standard set today.

i. NO_x Reductions

Today’s standards should result in about a 90 percent reduction in NO_x from new engines. Table II.B-4 presents these projections with the estimated NO_x benefits for selected years.

**Table II.B-4. Nationwide NO_x Emissions from HDDEs
(thousand short tons per year)**

<i>Calendar Year</i>	<i>Baseline</i>	<i>Controlled</i>		<i>Reduction</i>	
		<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>
2007	2,650	2,620	2,600	29	57
2010	2,440	2,020	2,040	416	403
2015	2,310	1,080	1,090	1,230	1,220
2020	2,350	582	587	1,770	1,760
2030	2,770	291	292	2,480	2,480

ii. PM Reductions from 2007 Model Year and Later

This section just looks at exhaust emission PM benefits that are directly the result of the 2007 standards. DSPM benefits are presented later. For engines meeting the new standards, we consider low sulfur fuel to be necessary to enable the PM control technology. In other words, we

don't claim additional emissions reductions beyond the standard due to reductions in direct sulfate PM except for the difference between certification and average in-use fuel sulfur levels as discussed above.

The new standards should result in about a 90 percent reduction in exhaust PM from new engines. This translates to a 76 percent reduction in total PM₁₀ when brake and tire wear are considered. Table II.B-5 presents these projections with the estimated PM benefits for selected years. This table includes brake and tire wear, but does not include the direct sulfate benefits from the existing fleet. These results do not change between the AQAC and Updated analyses.

Table II.B-5. Nationwide PM₁₀ Exhaust and Brake/Tire Wear Emissions from HDDEs Without Existing Fleet Reductions (thousand short tons per year)

<i>Calendar Year</i>	<i>Baseline Exhaust</i>	<i>Control Exhaust</i>	<i>Reduction</i>	<i>Brake/Tire Wear</i>
2007	96	91	5	13
2010	84	57	27	15
2015	80	28	51	17
2020	86	15	71	19
2030	104	8	96	23

iii. NMHC Reductions

Although the standards give manufacturers the same phase-in for NMHC as for NO_x, we model the NMHC reductions to be fully in place for diesel engines in 2007. As discussed earlier, we believe the use of aftertreatment for PM control will cause the NMHC levels to meet the standard as soon as the PM standard goes into effect in 2007, but in the *Updated Control Case*, no longer assume a 90 percent reduction due to the particulate trap. This standard will result in about a 30 percent reduction in NMHC from new engines. Table II.B-6 presents these projections with the estimated NMHC reductions for selected years.

**Table II.B-6. Nationwide NMHC Exhaust Emissions from HDDEs
(thousand short tons per year)**

<i>Calendar Year</i>	<i>Baseline</i>	<i>Controlled</i>		<i>Reduction</i>	
		<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>
2007	184	175	182	9	2
2010	185	132	172	53	13
2015	191	74	156	117	35
2020	206	40	152	166	54
2030	240	25	167	217	74

iv. Fuel Consumption Estimates

Table II.B-7 presents national fuel consumption estimates for HDDEs. Table II.B-8 presents our estimates of low sulfur fuel consumption. This total consumption includes on-highway fuel used by light duty diesel vehicles and spillover into sources other than on-highway. Our total consumption estimates are similar to EIA's production estimates and our highway fuel consumption estimates are consistent with Federal Highway Association estimates of taxed highway diesel fuel use.¹⁶⁰

Table II.B-7. HDDE Fuel Consumption Estimates by Calendar Year (billion gallons)

<i>Calendar Year</i>	<i>LHDDE</i>	<i>MHDDE</i>	<i>HHDDE</i>	<i>Urban Bus</i>
2007	4.26	5.57	26.4	0.86
2010	4.52	5.94	27.9	0.91
2015	4.93	6.53	30.4	0.99
2020	5.30	7.06	32.6	1.06
2030	5.95	8.02	36.5	1.18

Table II.B-8. Consumption of Highway Diesel Fuel Including Spillover (billion gallons)

<i>Calendar Year</i>	<i>Light-duty</i>	<i>Heavy-duty</i>	<i>Spillover</i>	<i>Total</i>
2007	0.37	37.1	4.09	41.5
2010	0.39	39.3	4.25	44.0
2015	0.43	42.8	4.51	47.8
2020	0.46	46.0	4.78	51.2
2030	0.53	51.6	5.30	57.5

v. *DSPM Reductions from Existing Fleet*

Figure II.B-1 shows our national projections (using the *Updated Control Case*) of direct sulfate PM emissions from the pre-2007 engines using HD highway diesel fuel with and without the low sulfur fuel. The low sulfur fuel should result in about a 95 percent reduction in direct sulfate PM from pre-2007 engines. Table II.B-9 presents the estimated DSPM benefits from HDDEs and other engines using the same fuel for selected years.

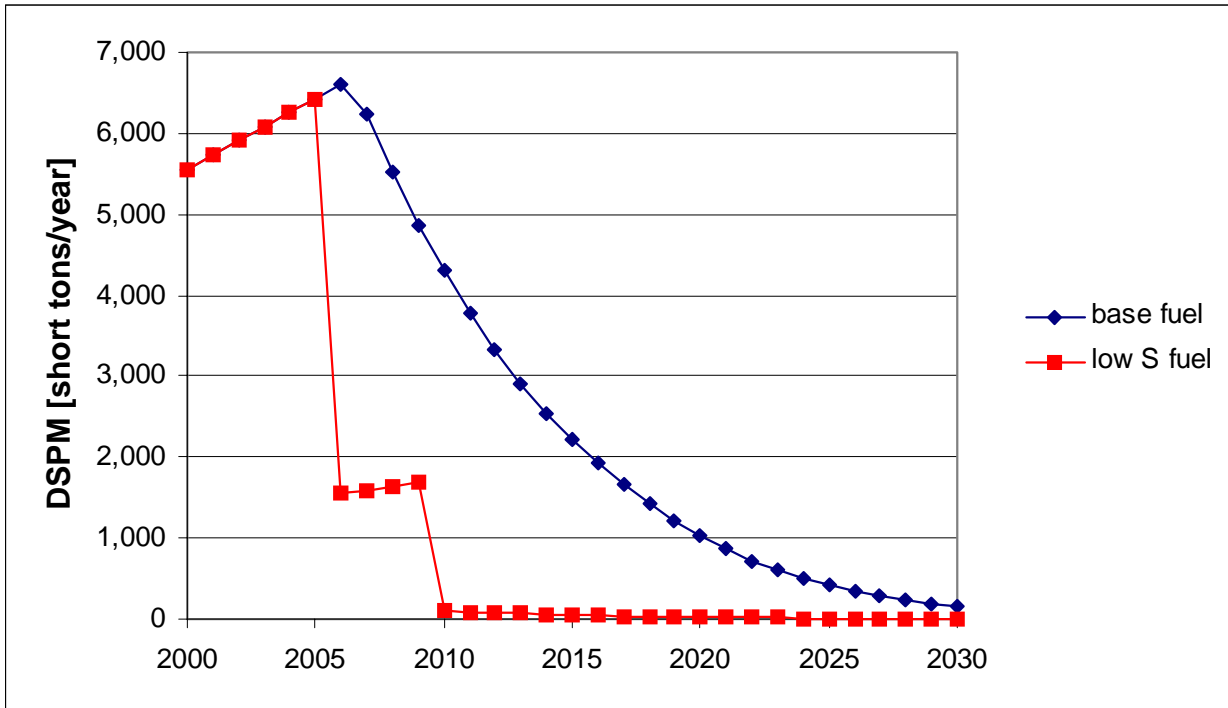


Figure II.B-1. Projected DSPM from Pre-2007 Engines Using Highway Diesel Fuel

Table II.B-9. Existing Fleet PM Reductions From Low Sulfur Fuel
(thousand short tons per year)

Calendar Year	HDDEs		Other		Total Reductions	
	AQAC	Updated	AQAC	Updated	AQAC	Updated
2007	6.07	4.64	0.73	0.56	6.80	5.20
2010	4.19	4.19	0.50	0.50	4.69	4.69
2015	2.16	2.16	0.25	0.25	2.41	2.41
2020	1.00	1.00	0.11	0.11	1.12	1.12
2030	0.15	0.15	0.02	0.02	0.17	0.17

vi. Crankcase Emission Reductions

Table II.B-10 presents our estimates of the baseline crankcase emissions from HDDEs. As described earlier, we assume that the crankcase emissions would be zero for the controlled case. These calculations do not differ between the AQAC and Updated analyses.

**Table II.B-10. Crankcase Emissions from Uncontrolled HDDEs
(thousand short tons per year)**

<i>Calendar Year</i>	<i>NOx</i>	<i>PM</i>	<i>NMHC</i>
2007	0.7	0.7	0.7
2010	3.7	3.7	3.7
2015	7.1	7.1	7.1
2020	9.5	9.5	9.5
2030	12.8	12.8	12.8

vii. Sum of NOx, PM, and NMHC Reductions

As discussed above, we are anticipating large emission reductions in NOx, PM, and NMHC from HDDEs as a result of the new exhaust emission standards. In addition, we are anticipating reductions in PM from the existing fleet due to the low sulfur fuel and reductions from 2007 and later MY engines due to the closed crankcase requirements. Table II.B-11 presents the total projected reductions from HDDEs for this rule for selected years.

**Table II.B-11. Total Reductions from HDDEs for this Rule
(thousand short tons per year)**

<i>Calendar Year</i>	<i>NOx</i>		<i>PM</i>		<i>NMHC</i>	
	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>
2007	29	58	13	11	10	2
2010	419	406	35	35	57	17
2015	1,240	1,230	61	61	124	43
2020	1,780	1,770	82	82	175	64
2030	2,490	2,490	109	109	229	87

This action is the second of two rules requiring large reductions in NOx emissions from HDDEs. The 2004 standards reduce NOx from 4 g/bhp-hr to about 2.3 g/bhp-hr. The new standards will reduce NOx again by another 2.1 g/bhp-hr in 2007. This is a 95 percent reduction in NOx from new engines. Figure II.B-2 presents (using the *Updated Control Case*) the combined effects of the two standards on national HDDE NOx emissions. This figure also includes crankcase emissions.

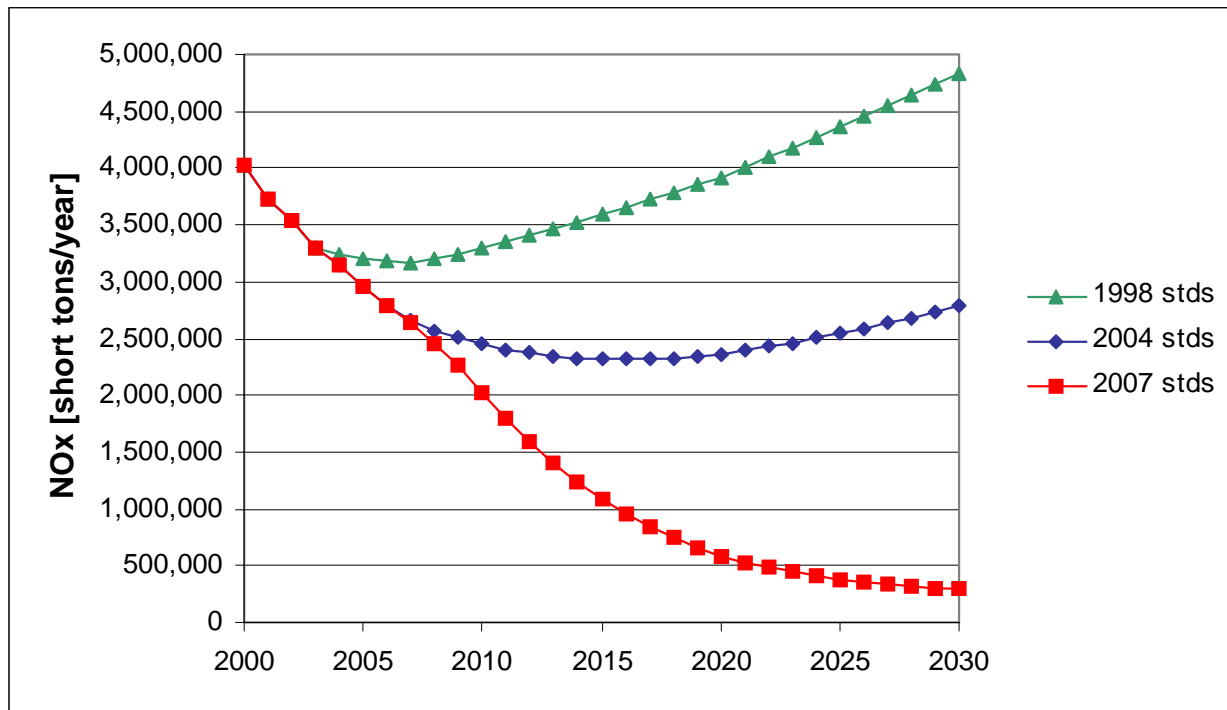


Figure II.B-2. Projected HDDE NOx Emissions Due to 2004 and 2007 Standards

Figure II.B-3 shows (using the *Updated Control Case*) our national projections of total PM emissions with and without the new engine controls. This figure includes brake and tire wear, crankcase emissions, and the direct sulfate PM benefits due to the use of low sulfur fuel by the existing fleet.

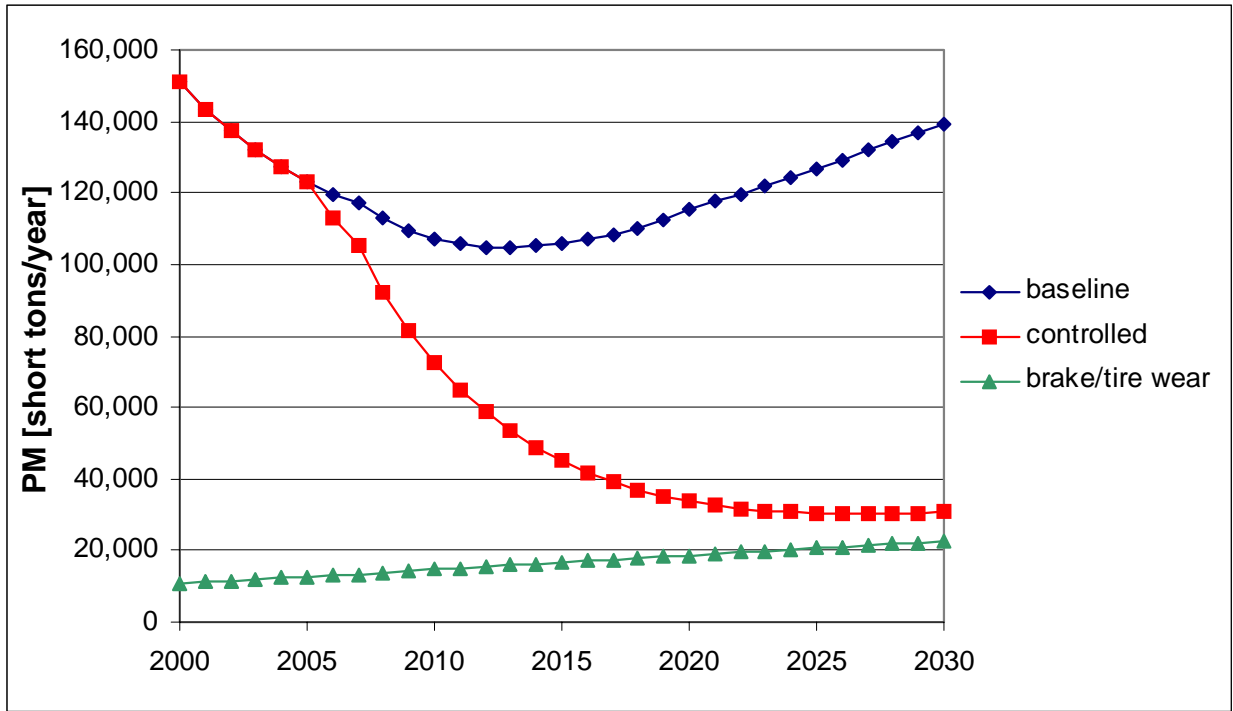


Figure II.B-3. Projected Nationwide PM Emissions from HDDEs

Figure II.B-4 shows (using the *Updated Control Case*) our national projections of total NMHC crankcase and exhaust emissions from HDDEs with and without the new engine controls.

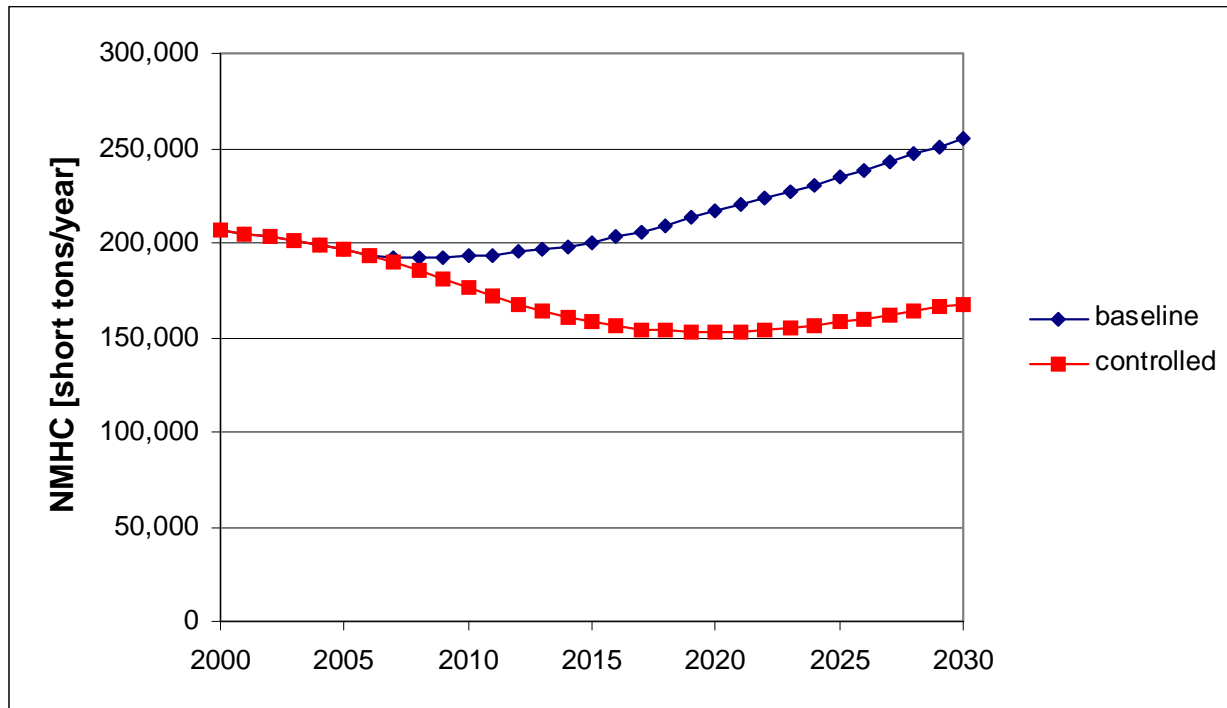


Figure II.B-4. Projected Nationwide NMHC Emissions from HDDEs

b. Additional Reductions due to the New HDDE Standards

This section looks at tons/year emission inventories of carbon monoxide (CO), oxides of sulfur (SOx), and air toxics from HDDEs. Although we are not including explicit new standards for these pollutants in today’s action, we believe the new standards will result in reductions in CO, SOx, and air toxics. Here we present our anticipated benefits.

i. CO Reductions

Although the CO standard for HDDEs remains at 37.1 g/bhp-hr, CO emission levels from certified HDDEs are much lower. According to the emission factor report¹⁶¹ we use for baseline EFs and DFs, baseline emissions for CO range from 1.0 to 1.3 g/bhp-hr for HDDEs. We believe that the exhaust emission control technology that would be used to meet the standards would result in excess of a 90 percent reduction in CO from baseline levels. This is because PM traps have very high oxidation capabilities. We use 90 percent here to be conservative. Using this assumption, Table II.B-12 presents projected reductions in CO from HDDEs. These results do not change between the AQAC and Updated analyses.

**Table II.B-12. Reductions in CO from HDDEs
(thousand short tons per year)**

<i>Calendar Year</i>	<i>CO Reduction</i>
2007	56
2010	317
2015	691
2020	982
2030	1,290

ii. *SOx Reductions*

We assume that all of the sulfur in the fuel not converted to direct sulfate PM is converted to sulfur dioxide. For pre-2007 engines, we assume that 98 percent of the sulfur is converted to SO₂; for 2007 and later engines, we assume that 70 percent of the sulfur is converted to SO₂. Because we are converting from S to SO₂, we use a molecular weight ratio of 64/32. Table II.B-13 presents our estimates of SOx reductions from HDDEs corresponding with the use of low sulfur fuel. Table II.B-13 also presents SOx benefits from other sources using highway diesel fuel as discussed earlier in this chapter.

**Table II.B-13. Reductions in SOx from Low Sulfur Fuel
(thousand short tons per year)**

<i>Calendar Year</i>	<i>HDDE SOx Reduction</i>		<i>Other SOx Reduction</i>	
	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>
2007	90	70	11	8
2010	96	96	12	11
2015	105	105	13	12
2020	113	113	13	13
2030	127	127	14	14

iii. *Air Toxic Reductions*

Table II.B-14 shows the estimated air toxics reductions associated with the anticipated reductions in hydrocarbons. The difference between the toxics reductions from the *Air Quality Analysis Case* and the *Updated Control Case* are due to the revised assumption about NMHC reductions due to PM traps.

**Table II.B-14. Reductions in Air Toxics from HDDEs
(thousand short tons per year)**

<i>Calendar Year</i>	<i>Benzene</i>		<i>Formaldehyde</i>		<i>Acetaldehyde</i>		<i>1,3-Butadiene</i>	
	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>
2007	0.14	0.02	1.02	0.18	0.38	0.07	0.08	0.01
2010	0.87	0.22	6.47	1.60	2.38	0.59	0.50	0.12
2015	2.01	0.61	15.0	4.52	5.52	1.66	1.17	0.35
2020	2.81	0.92	20.1	6.83	7.71	2.52	1.63	0.53
2030	3.80	1.30	28.3	9.70	10.4	3.57	2.21	0.76

3. HDGV Emission Reductions

This section presents reductions in NO_x, exhaust and evaporative NMHC, and air toxics from HDGVs that we anticipate from this rule. Although, medium-duty passenger vehicles (MDPV) are technically part of the HDGV class, they are not included in the standards finalized today. Therefore, emissions from MDPVs are not included in the inventories presented here. MDPVs were recently regulated under the Tier 2 light-duty vehicle rule.

Also, we do not claim benefits for reductions in California for HDGVs due to California's comparably stringent LEV2 standards for these vehicles. However, the charts presented below will include national inventories. In the tables, we will only present emissions reductions that we are claiming for this rule.

The *Air Quality Analysis Case* includes emissions from MDPVs in its baseline, and includes 50-state emissions reductions from the HDGVs regulated under this rule. Therefore, we also present an adjusted AQAC inventory which only includes HDGVs covered by this rule and distinguishes between 49-state and 50-state emission reductions. The *Updated Control Case* not only accounts for the difference between the proposed and final standards, but accounts for MDPVs and California reductions. All of the charts in this section are based on the *Updated*

Control Case; however, the tables present the AQAC (with and without MDPV emissions) and Updated (excludes MDPV emissions) results.

a. NOx Reductions

Figure II.B-5 presents the projected NOx inventory with and without the new standards. We believe the NOx standards will result in more than a 60 percent reduction in NOx from new heavy-duty gasoline vehicles. Tables II.B-15.a and II.B-15.b present these projections with the estimated NOx reductions for selected years for the AQAC and Updated inventories respectively. Table II.B-15a distinguishes between the inventory with and without medium duty passenger vehicles (MDPV). Although these vehicles are classified as HDGVs, they were included in the Tier 2 standards and therefore are not included in today’s standards. Table II.B-15b presents the Updated control case which considers a delay in the standards compared to the AQAC inventory. MDPV emissions are excluded from this table.

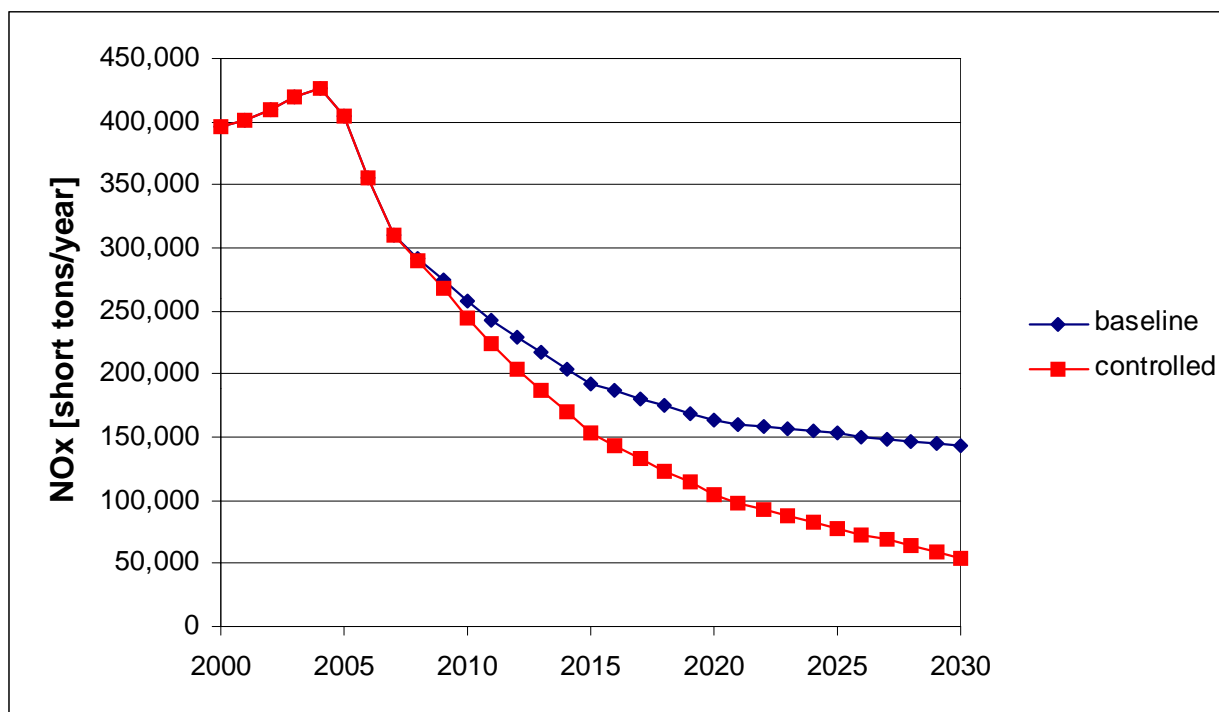


Figure II.B-5. Projected Nationwide Exhaust NOx Emissions from HDGVs

Table II.B-15.a. Estimated Nationwide NOx Emissions from HDGVs Based on the Air Quality Analysis Case (thousand short tons per year)

<i>Calendar Year</i>	<i>Baseline</i>		<i>Controlled</i>		<i>Reduction</i>	
	<i>AQAC</i>	<i>w/o MDPVs</i>	<i>AQAC</i>	<i>w/o MDPVs</i>	<i>50-state</i>	<i>49-state</i>
2007	381	310	377	306	4	3
2010	316	257	292	233	24	21
2015	236	192	187	144	48	43
2020	200	163	133	96	67	60
2030	175	143	81	49	94	84

Table II.B-15.b. Estimated Nationwide NOx Emissions from HDGVs Based on the Updated Control Case (thousand short tons per year)

<i>Calendar Year</i>	<i>Baseline</i>	<i>Controlled</i>	<i>Reduction</i>	
			<i>50-state</i>	<i>49-state</i>
2007	310	310	0	0
2010	257	244	13	12
2015	192	154	38	34
2020	163	105	58	52
2030	143	54	88	79

b. Exhaust NMHC Reductions

Figure II.B-6 presents the projected exhaust NMHC inventory with and without the new standards. We believe the NMHC standard will result in about a 30 percent reduction in exhaust NMHC from new heavy-duty gasoline vehicles. Tables II.B-16.a and II.B-16.b present these projections with the estimated exhaust NMHC reductions for selected years for the AQAC and Updated inventories.

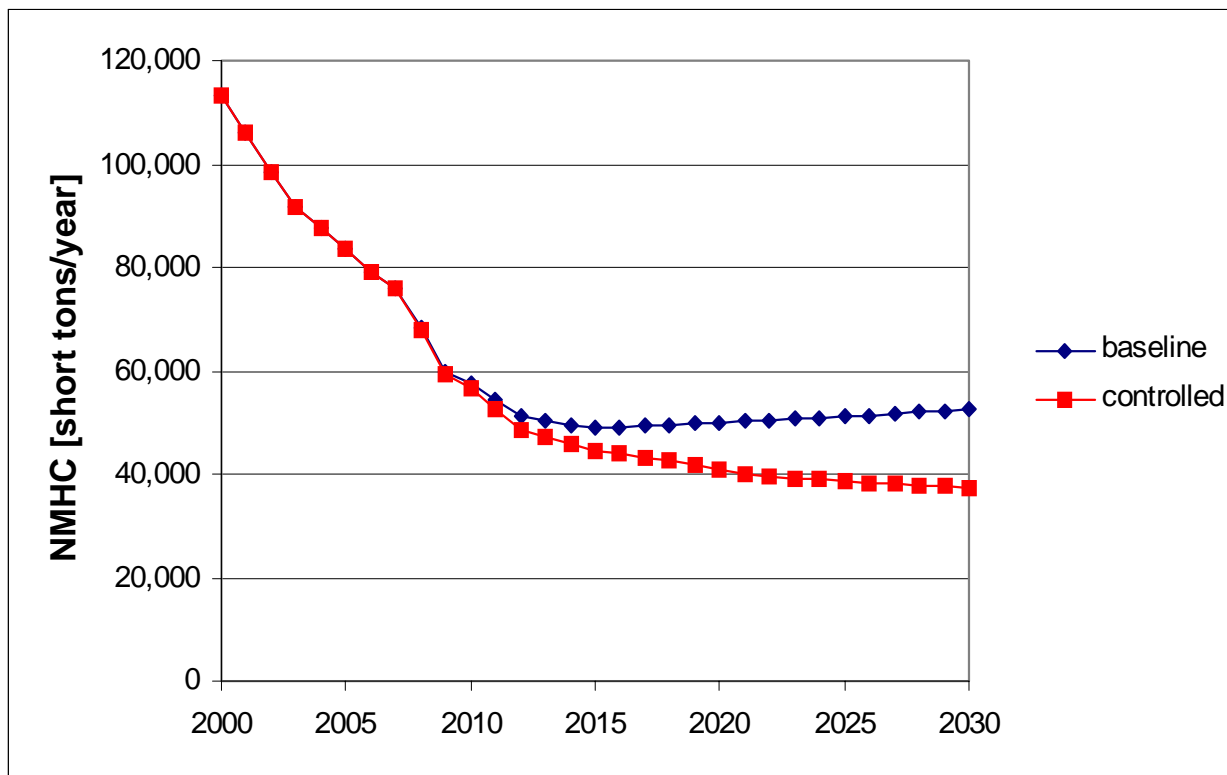


Figure II.B-6. Projected Nationwide Exhaust NMHC Emissions from HDGVs

Table II.B-16.a. Estimated Nationwide Exhaust NMHC Emissions from HDGVs Based on the Air Quality Analysis Case (thousand short tons per year)

Calendar Year	Baseline		Controlled		Reduction	
	AQAC	w/o MDPVs	AQAC	w/o MDPVs	50-state	49-state
2007	93	76	93	75	0.4	0.4
2010	71	58	68	55	2.4	2.1
2015	60	49	55	44	5.4	4.8
2020	61	50	51	39	10.5	9.4
2030	64	52	49	37	15.6	14.0

Table II.B-16.b. Estimated Nationwide Exhaust NMHC Emissions from HDGVs Based on the Updated Control Case (thousand short tons per year)

<i>Calendar Year</i>	<i>Baseline</i>	<i>Controlled</i>	<i>Reduction</i>	
			<i>50-state</i>	<i>49-state</i>
2007	76	76	0	0
2010	58	56	1.3	1.1
2015	49	45	4.4	3.9
2020	50	41	9.0	8.1
2030	52	37	15.0	13.5

c. Evaporative Emission Reductions

Evaporative HC emissions include diurnal, resting loss, refueling, and running loss emissions. To estimate evaporative emissions reductions from HDGVs, we used MOBILE5b to calculate percent reductions. We generated average national emission factors giving consideration to northern and southern regions of the country, fuel programs, inspection/maintenance programs, and time of year. This analysis uses the same methodology as was used in the inventory analysis for the Tier 2 light-duty vehicle standards.¹⁶²

Figure II.B-7 presents the projected nonexhaust HC inventory with and without the new standards. We believe the new evaporative emissions standards would result in about a 12 percent reduction in nonexhaust HC from new heavy-duty gasoline vehicles. Tables II.B-17.a and II.B-17.b present these projections with the estimated evaporative emission reductions for selected years for the AQAC and Updated inventories.

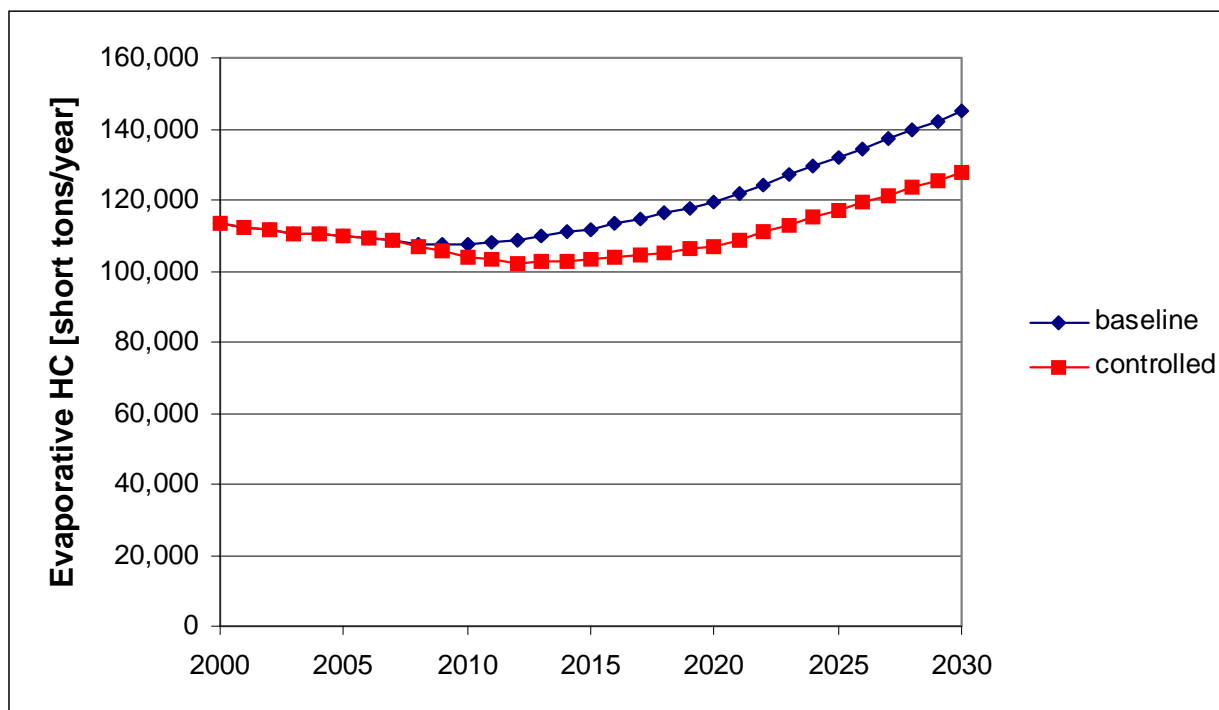


Figure II.B-7. Projected Nationwide Evaporative Emissions from HDGVs

Table II.B-17.a. Estimated Nationwide Evaporative Emissions from HDGVs Based on the Air Quality Analysis Case (thousand short tons per year)

Calendar Year	Baseline		Controlled		Reduction	
	AQAC	w/o MDPVs	AQAC	w/o MDPVs	50-state	49-state
2007	134	109	133	108	1	1
2010	132	107	126	102	6	5
2015	137	112	127	102	10	9
2020	146	119	133	106	13	12
2030	178	145	160	127	17	16

**Table II.B-17.b. Estimated Nationwide Evaporative Emissions from HDGVs
Based on the Updated Control Case (thousand short tons per year)**

<i>Calendar Year</i>	<i>Baseline</i>	<i>Controlled</i>	<i>Reduction</i>	
			<i>50-state</i>	<i>49-state</i>
2007	109	109	0.0	0.0
2010	107	104	3.4	3.0
2015	112	103	8.9	8.0
2020	119	107	12.2	10.9
2030	145	128	17.1	15.3

d. Air Toxics Reductions

The air toxics 49-state reductions for HDGVs are presented in Table II.B-18 for the *Air Quality Analysis Case* and the *Updated Control Case*.

**Table II.B-18. Estimated 49-State Reductions in Air Toxics from HDGVs
(thousand short tons per year)**

<i>Calendar Year</i>	<i>Benzene</i>		<i>Formaldehyde</i>		<i>Acetaldehyde</i>		<i>1,3-Butadiene</i>	
	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>	<i>AQAC</i>	<i>Updated</i>
2007	0.03	0.00	0.02	0.00	0.00	0.00	0.00	0.00
2010	0.24	0.14	0.12	0.06	0.03	0.02	0.02	0.01
2015	0.41	0.36	0.25	0.20	0.07	0.06	0.04	0.03
2020	0.46	0.42	0.29	0.25	0.09	0.08	0.04	0.03
2030	0.68	0.66	0.50	0.48	0.16	0.15	0.07	0.07

4. Total Emission Reductions

Figures II.B-8 through II.B-10 present the total projected emissions of NO_x, PM, and NMHC from heavy-duty engines with and without the new exhaust, evaporative, crankcase, and fuel sulfur standards. No reductions are assumed for HDGV PM. Tables II.B-19 through II.B-21

present the total NOx, PM, and NMHC benefits from heavy-duty engines that we anticipate from this rule. Evaporative emission reductions are included in the NMHC benefits. Table II.B-22 presents the total air toxics reductions. All of these projections are based on the *Updated Control Case*. Reductions in California are not included in the tables.

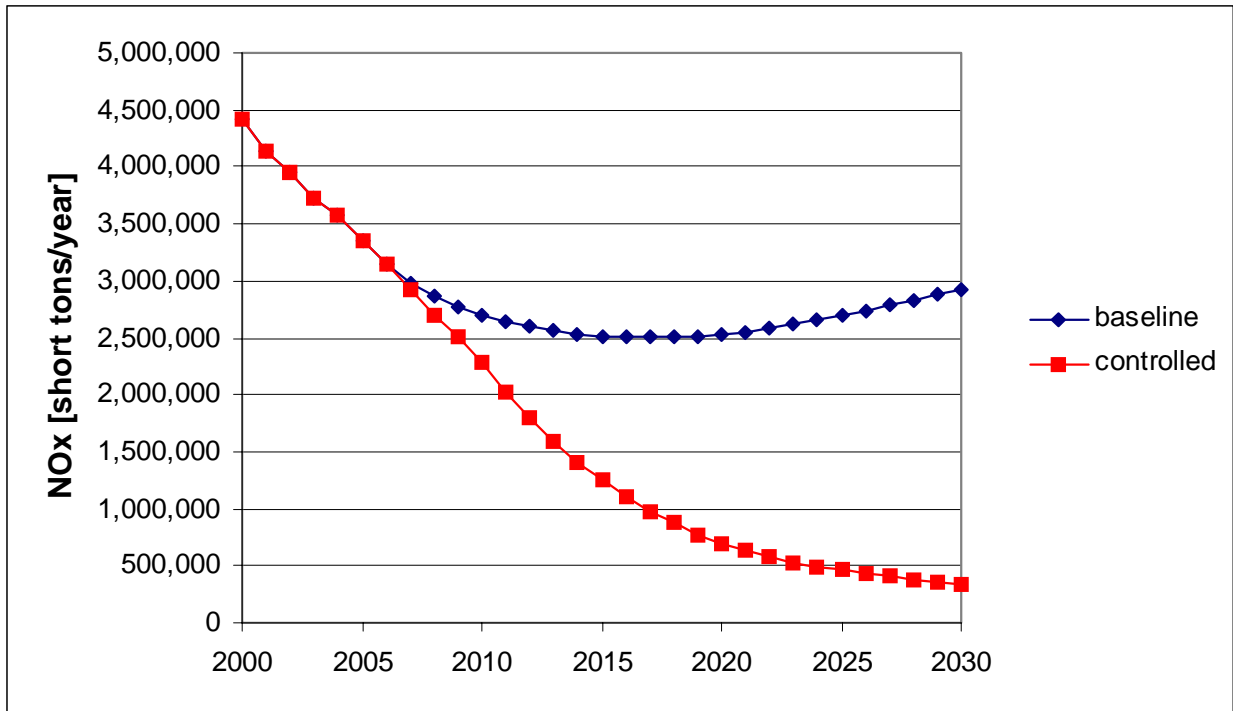


Figure II.B-8. Projected NOx Inventory for Heavy-Duty Highway Vehicles

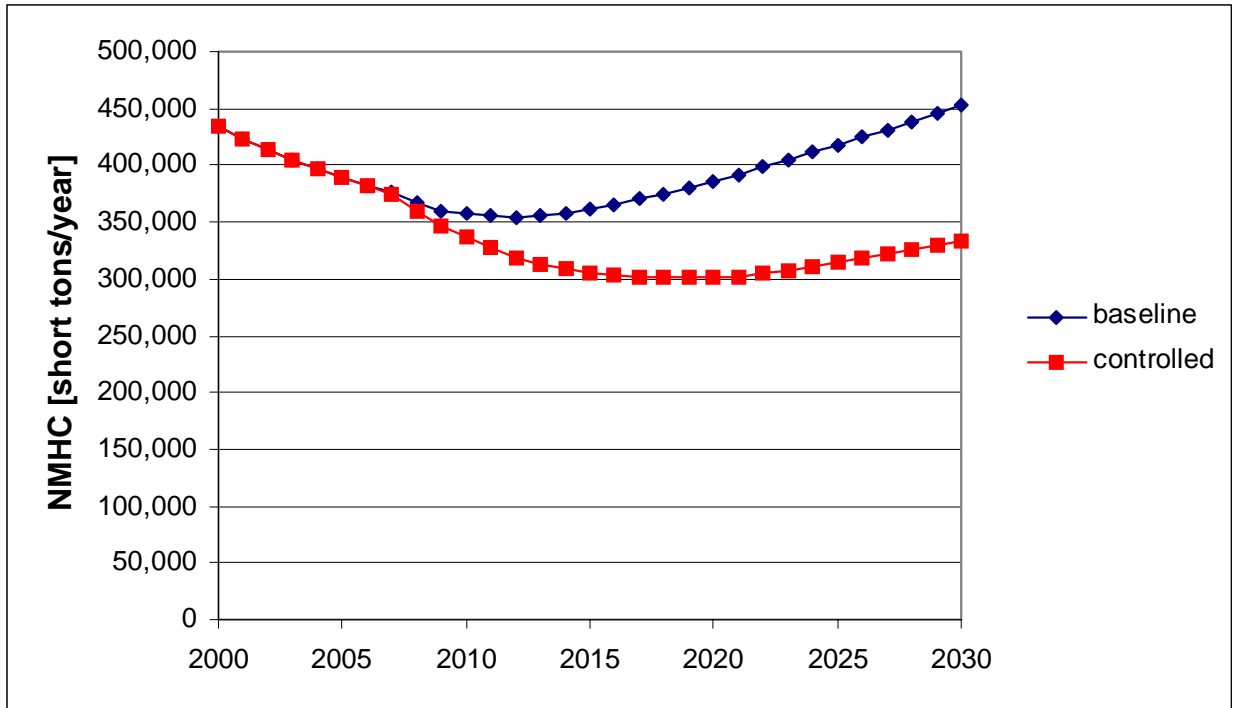


Figure II.B-10. Projected NMHC Inventory for Heavy-Duty Highway Vehicles

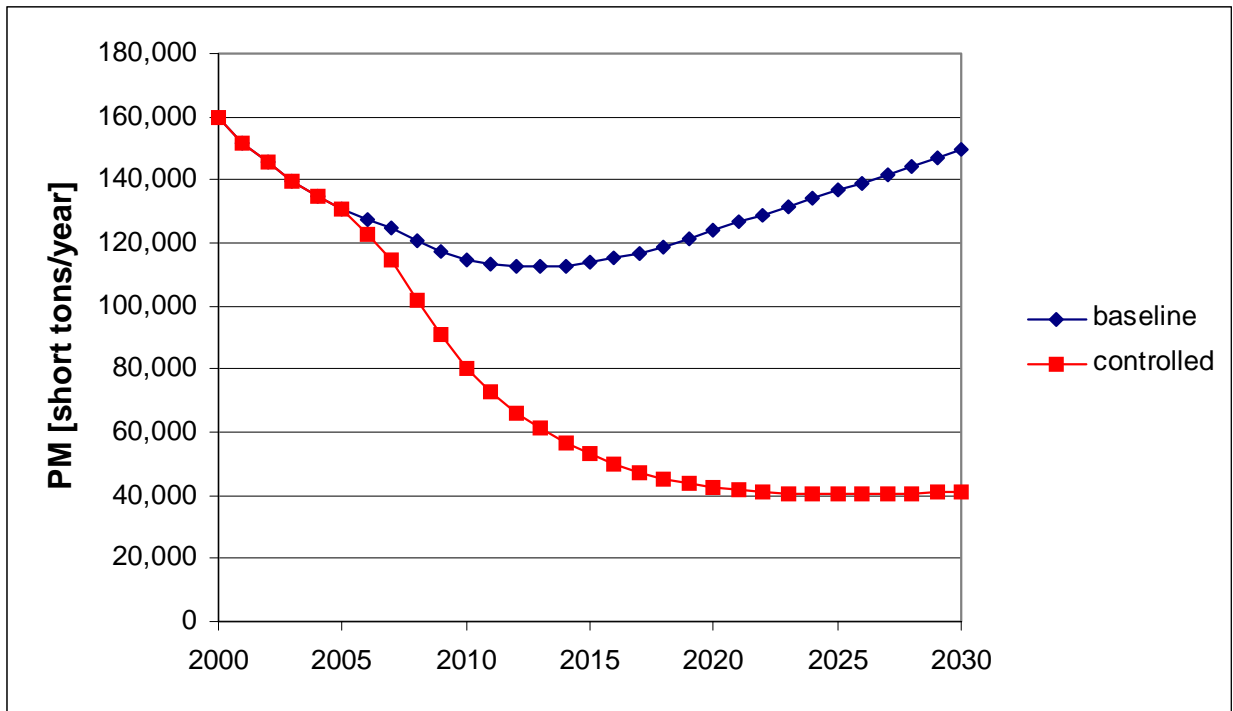


Figure II.B-9. Projected PM Inventory for Heavy-Duty Highway Vehicles

Table II.B-19. Total NOx Emissions and Benefits for This Rule
(thousand short tons per year)

<i>Calendar Year</i>	<i>HDV Baseline</i>	<i>HDV Controlled</i>	<i>Reduction</i>
2007	2,970	2,910	58
2010	2,710	2,290	420
2015	2,520	1,250	1,260
2020	2,520	692	1,820
2030	2,930	346	2,570

Table II.B-20. Total PM Emissions and Reductions for This Rule
(thousand short tons per year)

<i>Calendar Year</i>	<i>HDV Baseline</i>	<i>HDV Controlled</i>	<i>HDV Reduction</i>	<i>Other DSPM Reduction*</i>	<i>Total Reduction</i>
2007	125	114	11	0.6	12
2010	115	79	35	0.6	36
2015	114	53	61	0.6	61
2020	124	42	82	0.7	82
2030	150	41	109	0.7	109

* From sources other than HDDEs using on-highway low sulfur fuel.

**Table II.B-21. Total NMHC Emissions and Reductions for This Rule
(thousand short tons per year)**

<i>Calendar Year</i>	<i>HDV Baseline</i>	<i>HDV Controlled</i>	<i>Reduction</i>
2007	376	374	2
2010	358	337	21
2015	361	305	54
2020	386	301	83
2030	451	332	115

**Table II.B-22. Total Reductions in Air Toxics for This Rule
(thousand short tons per year)**

<i>Calendar Year</i>	<i>Benzene</i>	<i>Formaldehyde</i>	<i>Acetaldehyde</i>	<i>1,3-Butadiene</i>
2007	0.02	0.18	0.07	0.01
2010	0.36	1.67	0.61	0.14
2015	0.96	4.72	1.72	0.38
2020	1.34	7.08	2.60	0.57
2030	1.96	10.2	3.73	0.82

5. Differences from NPRM Inventory

For the NPRM we used a simplified analysis to calculate emissions inventories and reductions from heavy-duty vehicles. For HDDEs we took a top-down approach to modeling emission inventories using a spreadsheet model. For HDGVs we used emission factors generated using a modified MOBILE5 model with the inputs of an average speed, average fuel, and summertime average temperature. Neither of these approaches were sophisticated enough to include county-by-county or hour-by-hour effects on the emission inventories. With that being said, these inventories have proven to be similar to the FRM inventories.

The FRM inventories (as discussed above) are based on complex and time consuming calculations in which emissions were summed in every county in the U.S. on an hourly basis. These inventories were developed for 1996, 2007, 2020, and 2030. Mathematically, this bottom-

up approach gives us more precise results than using national averages. In addition, it allows us to account for more specific effects of ambient conditions, roadway types, fuel parameters, and scrappage rates on HDV emissions.

In this section, we compare the baseline emissions inventories from the NPRM to those presented in the FRM. By looking at baseline inventories we can focus on the calculation methodology separate from the differences caused by the changes in the FRM standards from the proposed standards. The effects of these changes are described in detail earlier in this chapter. We believe that the small changes between the NPRM and FRM inventories reflect better analysis in the FRM inventory.

a. Heavy-Duty Diesel Engines

i. MOBILE Model (NO_x, NMHC)

As discussed above, MOBILE5 was used with adjustment factors to calculate HDDE NO_x and NMHC in the final rule. The primary difference between the NPRM and FRM analyses is that we only considered operation at a single average speed in the NPRM spreadsheet analysis; therefore, no speed correction was made. However, for the FRM analysis, emissions were calculated for twelve different roadway types. These roadway type distributions differed for each county. Based on the national average distribution of roadway types reported in the FRM analysis, we can roughly calculate the effect of speed on NO_x and NMHC inventories. Using the MOBILE speed correction factors, we approximate that the weighted average national speed correction is -5 percent for NO_x and -17 percent for NMHC.

Table II.B-23 compares the NPRM and FRM inventories for exhaust NO_x and NMHC. We look at exhaust emissions only, because crankcase emissions are still calculated the same way in the FRM analysis as they were in the NPRM analysis. As shown in this table, most of the change from the NPRM to the FRM inventory is due to the application of speed correction factors. We also would expect variation between the two inventories due to the top-down versus bottom-up methodology as discussed earlier.

Table II.B-23. Comparison of NPRM and FRM HDDE Baseline Inventories for NOx and NMHC (thousand short tons per year)

<i>Calendar Year</i>	<i>Exhaust NOx</i>			<i>Exhaust NMHC</i>		
	<i>NPRM</i>	<i>FRM</i>	<i>% Change</i>	<i>NPRM</i>	<i>FRM</i>	<i>% Change</i>
2007	2,860	2,650	-7%	218	184	-16%
2020	2,600	2,350	-10%	249	206	-17%
2030	3,000	2,770	-8%	292	240	-18%

ii. *PART Model (PM, SOx)*

As discussed above, PART5 was used with adjustment factors to calculate HDDE PM and SOx in the final rule. Table II.B-24 shows very good correlation in exhaust PM and SOx between the NPRM and FRM inventories. In this case, the FRM results are less sensitive to roadway distribution because PART does not apply speed correction factors to PM and SOx. We look at exhaust PM because the NPRM inventory did not include brake and tire wear. In addition, we use the same analysis methodology to calculate crankcase emissions in the NPRM and FRM.

Table II.B-24. Comparison of NPRM and FRM HDDE Baseline Inventories for Exhaust PM and SOx (thousand short tons per year)

<i>Calendar Year</i>	<i>Exhaust PM</i>			<i>Exhaust SOx</i>		
	<i>NPRM</i>	<i>FRM</i>	<i>% Change</i>	<i>NPRM</i>	<i>FRM</i>	<i>% Change</i>
2007	92	96	4%	91	92	2%
2020	88	86	-2%	112	116	4%
2030	106	104	-2%	126	130	4%

b. **Heavy-Duty Gasoline Vehicles**

As with the HDDE final analysis, the FRM bases the HDGV NOx and NMHC emissions inventories on the MOBILE5 model with adjustment factors. In this case, the NPRM was also based on MOBILE5 model runs with adjustments to the model year emission factors entered into the model. However, the NPRM analysis was run for a typical summer day and for a single speed of 20 mph. In addition, the NPRM did not consider the effects of inspection/maintenance

or reformulated fuel programs. As a result, we saw similar results as with the Tier 2 Inventory Analysis in which NMHC decreased noticeably with the county-by-county, hour-by-hour analysis compared to the more simple top down analysis.

Table II.B-25 compares the FRM and NPRM baseline inventories for NOx and NMHC. To make a direct comparison, we adjusted the NPRM inventory to be a national inventory rather than just a 49-state inventory. We believe that the differences in the inventories reflect more precise calculations in the county level analysis which results in a better inventory for the FRM.

Table II.B-25. Comparison of NPRM and FRM HDGV Baseline Inventories for NOx and NMHC (thousand short tons per year)

<i>Calendar Year</i>	<i>Exhaust NOx</i>			<i>Exhaust and Evaporative NMHC</i>		
	<i>NPRM</i>	<i>FRM</i>	<i>% Change</i>	<i>NPRM</i>	<i>FRM</i>	<i>% Change</i>
2007	307	310	1%	216	185	-15%
2020	159	163	2%	196	169	-14%
2030	138	143	3%	230	197	-14%

6. Sensitivity Analysis for In-Use PM Deterioration

In our analysis of the HDDE emissions inventory, we may underestimate emissions, especially PM, due to engine deterioration in-use. We believe that current modeling represents properly maintained engines, but may not be representative of in-use tampering or malmaintenance. However, data related to this issue is extremely limited and inconclusive and we are in the process of collecting more data on in-use emission deterioration. Once this has been completed we will be better able to decide whether or not we need to update our deterioration rates. If we do update our deterioration rates, we will do so through a similar public process as we are using to create the MOBILE6 model.

Although a substantial amount of work remains before we can update our deterioration factors, we believe it is valuable to get a feel for the potential effects of in-use tampering and malmaintenance on the PM emissions inventory. In this section, we present a sensitivity analysis of these effects.

a. Methodology

Engine, Fuel, and Emissions Engineering, Inc. recently performed a study which suggests that tampering and malmaintenance result in large increases in in-use PM emissions from heavy-

duty diesel engines.¹⁶³ The California Air Resources Board (ARB) uses the underlying data in this report in developing its in-use deterioration rates for the EMFAC2000 emission model.¹⁶⁴ The ARB HDDE deterioration rates are presented in Table II.B-26 and are compared to the deterioration factors used in our inventory analysis. No deterioration is assumed for urban buses.

To perform our sensitivity analysis, we use the ARB deterioration rates and the NPRM spreadsheet model to determine the increases in the HDDE exhaust PM inventory due to tampering and malmaintenance. We then applied these increases to the exhaust PM inventory presented above. For 2007 and later model year engines, we assumed that the ratio of the deterioration rate to the emission standard is the same as for 2004 model year engines.

Table II.B-26. Comparison of EMFAC2000 and EPA PM Deterioration Rates for HDDEs (grams per mile per 10,000 miles)

<i>Model Year</i>	<i>EMFAC2000</i>			<i>EPA Analysis</i>		
	<i>LHDDE</i>	<i>MHDDE</i>	<i>HHDE</i>	<i>LHDDE</i>	<i>MHDDE</i>	<i>HHDE</i>
Pre 1976	0.003	0.016	0.016	0.000	0.000	0.000
1977-79	0.003	0.016	0.017	0.000	0.000	0.000
1980-83	0.004	0.016	0.018	0.000	0.000	0.000
1984-86	0.004	0.021	0.012	0.000	0.000	0.000
1987	0.005	0.017	0.008	0.000	0.000	0.000
1988-99	0.005	0.017	0.008	0.001	0.004	0.005
1990	0.005	0.017	0.008	0.000	0.000	0.000
1991-93	0.002	0.022	0.009	0.000	0.002	0.000
1994-97	0.003	0.018	0.010	0.000	0.002	0.000
1998	0.003	0.012	0.007	0.000	0.000	0.000
1999-02	0.001	0.012	0.003	0.000	0.000	0.000
2003	0.001	0.009	0.003	0.000	0.000	0.000
2004	0.001	0.009	0.003	0.000	0.000	0.000

b. Results

If we consider the EMFAC2000 deterioration rates presented in Table II.B-26, we see an increase of over 50 percent in the HDDE exhaust PM emission inventory compared to the results from the *Updated Control Case*. In 2030, we see an increase in the baseline PM inventory of 48 percent and an increase in the controlled PM inventory of 63 percent. This translates to an exhaust PM reduction of 141,000 tons in 2030 due to the new standards compared to the 96,000 ton PM reduction when tampering and malmaintenance were not considered. Figure II.B-11 presents the exhaust PM inventory with (“High”) and without (“FRM”) considering tampering and malmaintenance.

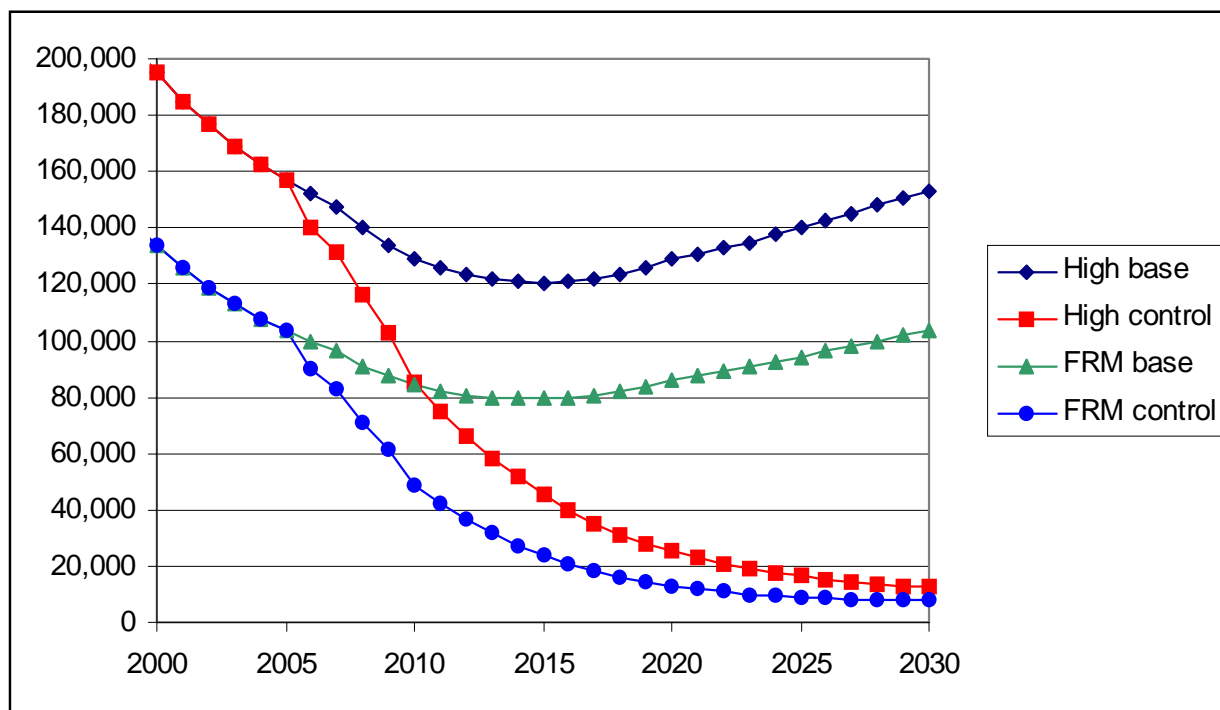


Figure II.B-11. Projected HDDE Exhaust PM Inventory with and without Consideration of Tampering and Malmaintenance

7. Contribution of HDVs to National Inventory

Nationwide, heavy-duty vehicles are projected to contribute about 15 percent of the total NOx inventory, and 28 percent of the mobile source inventory in 2007. Heavy-duty NOx emissions also contribute to fine particulate concentrations in ambient air due to the transformation in the atmosphere to nitrates. The NOx reductions resulting from today’s standards will therefore have a considerable impact on the national NOx inventory. All highway vehicles account for 34 percent and heavy-duty highway vehicles account for 20 percent of the mobile source portion of national PM₁₀ emissions in 2007. These inventories are based on the analysis performed by Pechan used for the air quality modeling analysis.^{165 166} Because this inventory analysis does not include stationary source emissions from Alaska and Hawaii, Tables II.B-27 through II.B-29 present emissions inventories for the 48 contiguous states.

**Table II.B-27. 2007 Baseline Emissions Inventories for 48 Contiguous States
(thousand short tons)**

<i>Source</i>	<i>VOC</i>	<i>NO_x</i>	<i>SO₂</i>	<i>PM*</i>	<i>CO</i>
Heavy-Duty Vehicles	415 (3%)	3,030 (15%)	94 (1%)	126 (4%)	3,850 (4%)
Light-Duty Vehicles	2,600 (18%)	2,950 (14%)	25 (0%)	82 (3%)	39,300 (42%)
Nonroad	2,120 (15%)	4,710 (23%)	1,040 (6%)	408 (14%)	27,200 (29%)
Other	9,140 (64%)	9,890 (48%)	15,900 (93%)	2,210 (78%)	22,600 (24%)
Total	14,300	20,600	17,100	2,830	92,900

* excludes natural and miscellaneous sources

**Table II.B-28. 2020 Baseline Emissions Inventories for 48 Contiguous States
(thousand short tons)**

<i>Source</i>	<i>VOC</i>	<i>NO_x</i>	<i>SO₂</i>	<i>PM*</i>	<i>CO</i>
Heavy-Duty Vehicles	420 (3%)	2,550 (14%)	118 (1%)	126 (4%)	4,720 (4%)
Light-Duty Vehicles	1,800 (13%)	1,310 (7%)	31 (0%)	100 (3%)	44,600 (42%)
Nonroad	2,000 (14%)	4,040 (23%)	1,310 (8%)	450 (15%)	33,900 (32%)
Other	10,100 (70%)	9,980 (56%)	14,500 (91%)	2,380 (78%)	23,700 (22%)
Total	14,300	17,900	16,000	3,060	107,000

* excludes natural and miscellaneous sources

**Table II.B-29. 2030 Baseline Emissions Inventories for 48 Contiguous States
(thousand short tons)**

<i>Source</i>	<i>VOC</i>	<i>NO_x</i>	<i>SO₂</i>	<i>PM*</i>	<i>CO</i>
Heavy-Duty Vehicles	491 (3%)	2,940 (16%)	133 (1%)	152 (5%)	5,730 (5%)
Light-Duty Vehicles	1,950 (12%)	1,250 (7%)	35 (0%)	114 (3%)	51,200 (42%)
Nonroad	2,230 (14%)	4,320 (23%)	1,490 (9%)	511 (15%)	39,200 (33%)
Other	11,000 (70%)	10,200 (55%)	14,800 (90%)	2,560 (77%)	24,400 (20%)
Total	15,700	18,700	16,400	3,340	120,000

* excludes natural and miscellaneous sources

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Chapter III: Emissions Standards Feasibility

For the past 30 or more years, emission control development for gasoline vehicles and engines has concentrated most aggressively on exhaust emission control devices. These devices currently provide as much as or more than 95 percent of the emission control on a gasoline vehicle. In contrast, the emission control development work for diesels has concentrated on improvements to the engine itself to limit the emissions leaving the combustion chamber.^a

However, during the past 15 years, more development effort has been put into diesel exhaust emission control devices, particularly in the area of particulate matter (PM) control. Those developments, and recent developments in diesel NO_x exhaust emission control devices, make the widespread commercial use of diesel exhaust emission controls feasible. Through use of these devices, we believe emissions control similar to that attained by gasoline applications will be possible with diesel applications. However, without low sulfur diesel fuel, these technologies cannot be implemented on heavy-duty diesel applications. Low sulfur diesel fuel will at the same time also allow these technologies to be implemented on light-duty diesel applications.

Several exhaust emission control devices have been developed to control harmful diesel PM constituents—the diesel oxidation catalyst (DOC), and the many forms of diesel particulate filters, or traps. DOCs have been shown to be durable in-use, but they control only a relatively small fraction of the total PM and, consequently, do not address our PM concerns sufficiently. Uncatalyzed diesel particulate filters demonstrated high efficiencies many years ago, but the level of the PM standard was such that it could be met through less costly “in-cylinder” control techniques. Catalyzed diesel particulate filters (CDPF, also referred to as catalyzed filters or catalyzed traps, along with the very similar continuously regenerating DPF or CR-DPF) have the potential to provide major reductions in diesel PM emissions and provide the durability and dependability required for diesel applications. Throughout this document we will use the acronym CDPF to refer to both catalyzed diesel particulate filters and the similar continuously regenerating diesel particulate filter. Because of the significant PM reductions that they enable and their proven durability on low sulfur diesel fuel, we believe the CDPF will be the control

^a Note that throughout this document we refer to diesel and gasoline vehicles and engines. We tend to use those terms given the preponderance of vehicles using diesel fuel or gasoline fuel in the U.S. heavy-duty highway market. However, when we refer to a diesel engine, we mean any engine using the diesel cycle. When we refer to a gasoline engine or vehicle, we mean any Otto-cycle vehicle or engine. Therefore, the emission standards discussed throughout this preamble apply equally to engines and vehicles fueled by alternative fuels, unless otherwise specified in the regulatory text accompanying today’s rule.

technology of choice for the future control of diesel PM emissions. However, CDPFs cannot be brought to market on diesel applications without low sulfur diesel fuel.

In addition to the diesel PM control devices, several exhaust emission control devices also have been developed to control diesel NO_x. For reasons discussed in this chapter, we believe that the NO_x adsorber is the most likely candidate to be used to meet future low diesel exhaust emission standards on the variety of applications in the heavy-duty diesel market. While other technologies exist that have the potential to provide significant emission reductions, such as selective catalytic reduction systems for NO_x control, we believe that the NO_x adsorber will likely be the only broadly applicable technology choice by the makers of engines and vehicles for the national fleet in the 2007-2010 time frame. Neither of the technologies for NO_x control discussed here, the NO_x adsorber or the compact SCR, can meet the Phase 2 standards without low sulfur diesel fuel.^b

As for gasoline engines and vehicles, improvement continues to be made to gasoline emissions control technology. This includes improvement to catalyst designs in the form of improved washcoats and improved precious metal dispersion. Much effort has also been put into improved cold start strategies that allow for more rapid catalyst light-off. This can be done by retarding the spark timing to increase the temperature of the exhaust gases, and by using air-gap manifolds, exhaust pipes, and catalytic converter shells to decrease heat loss from the system.

These improvements to gasoline emission controls will be made in response to the California LEV-II standards and the federal Tier 2 standards. These improvements should transfer well to the heavy-duty gasoline segment of the fleet. With such migration of light-duty technology to heavy-duty vehicles and engines, we believe that considerable improvements to heavy-duty gasoline emissions can be realized, thus allowing vehicles to meet much more stringent standards than currently required.

The following discussion provides more detail on the technologies which are capable of achieving the emission standards contained in this final rule. The purpose of this Chapter is to discuss the emission reduction capability of these emission control technologies, as well as discuss their sensitivity to sulfur in diesel fuel. We start with diesel applications, the technology expected and its need for low sulfur diesel fuel, and finish with gasoline applications.

^b The Phase 1 heavy-duty diesel standards are those required in 65 FR 59896, October 6, 2000, and are often referred to as the "2004 standards." The standards required for 2007 and later model year engines, promulgated in this rule represent Phase 2.

A. Feasibility of the Heavy-Duty Diesel Standards

1. Engine Out Improvements

Diesel engines have made great progress in lowering engine out emissions from 6.0 g/bhp-hr NO_x and 0.6 g/bhp-hr PM in 1990 to 4.0 g/bhp-hr NO_x and 0.1 g/bhp-hr PM in 1998. These reductions came initially with improvements to combustion and fuel systems. Introduction of electronic fuel systems in the early 1990s allowed lower NO_x and PM levels without sacrificing fuel economy. This, combined with increasing fuel injection pressures, have been the primary technologies that have allowed emission levels to be reduced to current levels.

Further engine out NO_x reductions to the levels necessary to comply with the Phase 1 standard of 2.5 g/bhp-hr NO_x+NMHC will come primarily from the addition of cooled exhaust gas recirculation (EGR). EGR recirculates a portion of the exhaust back to the intake manifold where it is drawn into the combustion chamber. The earliest EGR systems were uncooled. The recirculation of the hot exhaust gases to the intake manifold had the undesirable result of increasing the intake manifold temperature. This temperature rise reduces the NO_x reduction potential of uncooled EGR since the NO_x formation rate is proportional to temperature.¹ The intake manifold temperature rise also reduces the density of the fresh intake air, thus reducing the mass of fresh air drawn into the combustion chamber which lowers the air-fuel ratio. Lower air-fuel ratios generally increase PM emissions because there is less available oxygen to fully combust the carbon.

To overcome the lower air-fuel ratio and intake air density, the EGR gas can be cooled and/or the turbocharger can be adjusted to a higher pressure ratio. Both of these will almost certainly be done, but the latter tends to increase the work required of the turbocharger which increases fuel consumption. The former, cooling the recirculated exhaust gases, is limited by condensation concerns since a significant portion of the exhaust gases is water vapor.² The water vapor generally contains sulfuric acid as a result of the combustion of fuel-borne sulfur. This combustion results in SO₂ in the exhaust gas which can react with excess oxygen and water to form sulfuric acid (H₂SO₄). The level of EGR cooling is thus limited by the desire to prevent condensation of this corrosive water and sulfuric acid mixture. Therefore, the intake manifold temperature in an EGR equipped engine, even a cooled EGR engine, is usually higher than that found in a non-EGR engine.

More sophisticated electronic control systems will be necessary to control the EGR system and turbo machinery. EGR control algorithms will require additional engine condition information, possibly including mass air flow, oxygen, NO_x, or EGR valve position sensors. These inputs will be necessary to control the EGR rate via an EGR valve or possibly a variable geometry turbocharger (VGT). These turbochargers will also require a sophisticated control algorithm to take advantage of their transient response, EGR pumping, and air flow control

characteristics. In addition, the turbo machinery used with EGR will likely be pushed near the limits of its capability, and the engine's electronic control module (ECM—the engine's control computer) will need to ensure the limits of the hardware are not exceeded. Consequently, the Phase 1 heavy-duty diesel standards are expected to dramatically increase the capabilities of future ECMs compared to current non-EGR equipped ECMs.

We believe that reductions in engine out emissions beyond the Phase 1 levels may be attainable with low sulfur diesel fuel and more experience with cooled EGR systems. Low sulfur fuel will allow more EGR to be used at lower temperatures because of the reduced threat of sulfuric acid formation. In addition, recirculating the exhaust gases from downstream of a CDPF may allow different EGR pumping configurations to be feasible. Current EGR systems draw exhaust gases from the exhaust manifold upstream of the turbocharger turbine and recirculate them through the EGR cooler and into the intake manifold downstream of the turbo compressor and aftercooler. Such a system is called a high pressure loop EGR system because the gases are drawn from high pressure upstream of the turbo turbine and recirculated to high pressure downstream of the turbo compressor and aftercooler.

By contrast, a low pressure loop EGR system could draw some exhaust gases from the exhaust downstream of the turbo turbine and any exhaust emission control devices and recirculate those gases through the aftercooler and into the air intake system upstream of the compressor. The low pressure loop approach increases the effectiveness of the EGR system because it eliminates the high pressure loop EGR system's dependency on the pressure variations that exist between the intake and exhaust manifolds. To date, low pressure loop EGR has not been considered viable for HD applications because of the potential durability concerns associated with recirculating exhaust gas containing particles and sulfuric acid through the turbocharger compressor and aftercooler. The particles and acid accumulate in the aftercooler (typically made of aluminum) plugging and corroding it. The turbocharger compressor is also subject to particulate buildup and corrosion. But, by adding a CDPF and low sulfur fuel, the particles and acid would be reduced significantly and these durability concerns would be minimized.

Low pressure loop EGR systems provide many advantages over high pressure loop EGR systems. For example, low pressure loop EGR allows more EGR to be pumped across a wider engine operating range than with some other EGR configurations. As already pointed out, the EGR does not have to be pumped against changing turbocharger pressure differentials found in high pressure loop EGR systems that pump exhaust from the exhaust manifold upstream of the turbocharger turbine through an EGR cooler to the intake manifold. For promoting EGR, the pressure differential between the exhaust and intake manifolds can vary from very favorable at rated speed to very unfavorable near torque peak. The unfavorable pressure differential near torque peak requires work (i.e., pumping work) to be done to provide EGR during such engine operation, thereby causing a fuel economy penalty. However, the low pressure loop EGR system

is not dependent on the pressure differential characteristics of the turbocharger, meaning that it does not require this additional EGR pumping work. Therefore, we believe low pressure loop systems may allow increased EGR rates, improved fuel economy, and perhaps even further reductions of engine out emissions. However, these potential engine out emission reductions are expected to be modest and are not expected to be sufficient to meet the emission standards required by this final rule.

2. Meeting the PM Standard

Diesel PM consists of three primary constituents: elemental carbon particles from incomplete combustion, which make up the largest portion of the total PM; the soluble organic fraction (SOF), which consists of unburned hydrocarbons that have condensed into liquid droplets or have adsorbed onto the surfaces of the elemental carbon particles; and sulfates with associated water, which result from oxidation of fuel-borne sulfur in the engine's exhaust.

Several exhaust emission control devices have been developed to control diesel PM constituents -- the diesel oxidation catalyst (DOC), and the many forms of PM filters, CDPFs, or PM traps. DOCs have been shown to be durable in use, but they effectively control only the SOF portion of the total PM which, especially on today's engines, constitutes only around 10 to 30 percent of the total PM. Therefore, the DOC alone is not capable of meeting the FTP 0.01 g/bhp-hr PM standard set in this final rule.

Only the catalyzed diesel particulate filter (CDPF) is capable of providing the level of control required to meet the Phase 2 standards. In the past, the CDPF has demonstrated high trapping efficiency, but regeneration of the collected PM has been a serious challenge, when operating on anything other than low sulfur diesel fuel. The CDPF works by passing the exhaust through a ceramic or metallic filter to collect the PM. The collected PM, mostly elemental carbon particles but also a fraction of the SOF portion of PM at some low temperature conditions, must then be burned off the CDPF before the filter becomes plugged. This burning off of collected PM is referred to as "regeneration." The CDPF demonstrated high PM trapping efficiencies many years ago, but the level of the applicable PM standard was such that it could be met through less costly "in-cylinder" control techniques. As a result, the CDPF found little use in the diesel market. The un-catalyzed diesel particulate filter is unlikely to be able to meet the 0.01 g/bhp-hr PM standard as they are only moderately effective at controlling the SOF fraction of the PM. In addition, they require active regeneration technology which must be engaged frequently making the systems expensive to operate (i.e., increasing fuel consumption) and less reliable.

a. Catalyzed Diesel Particulate Filters

We believe the kind of diesel particulate filter that will be able to meet the PM standard in a reliable, durable, cost effective manner, and the type of diesel particulate filter that will prove to be the industry's technology of choice, is one capable of regenerating on an essentially continuous basis such as the catalyzed diesel particulate filter or CDPF. These CDPFs will be able to achieve very low PM emissions because:

- they are highly efficient at trapping all forms of diesel PM;
- they employ precious metals to reduce the temperature at which regeneration occurs, thereby allowing for passive regeneration under normal operating conditions typical of a diesel engine;^c
- they have lower average back-pressure thereby reducing potential fuel economy impacts, because they regenerate on a continuous basis; and,
- they need no extra burners or heaters as would be required by an active regeneration system, thereby reducing potential fuel economy impacts.

These CDPFs are able to provide in excess of 90 percent control of diesel PM, provided they are operated on diesel fuel with sulfur levels at or below 15 ppm. High sulfur level diesel fuel creates two problems for CDPFs. First, the CDPF cannot regenerate properly with current fuel sulfur levels as such sulfur levels poison the catalyst inhibiting the NO to NO₂ reaction severely limiting regeneration of the trapped PM.³ Second, because SO₂ is readily oxidized to SO₃ across the precious metals catalysts used in CDPFs, the Supplemental Emission Test (SET) 0.01 g/bhp-hr PM standard contained in today's final rule cannot be achieved with diesel fuel sulfur levels greater than 15 ppm because of the resultant increase in sulfate PM emissions ("sulfate make"). Table III.A-1 shows that at a 15 ppm sulfur level, a CDPF can achieve 0.009 g/bhp-hr over the Supplemental Emission Test (SET), but at 30 ppm sulfur, the SET results are 0.017 g/bhp-hr, which would exceed the standard. See the discussion later in this chapter for further information on CDPFs and sulfur, in particular section III.A.7.a.ii, "Loss of PM Control Effectiveness."

More than one emission control manufacturer is developing these precious metal catalyzed, passively regenerating CDPFs. In field trials, they have demonstrated highly efficient PM control and promising durability. A recent publication documents results from a sample of these field test engines after years of use in real world applications.⁴ The sampled CDPFs had on

^c For CDPF regeneration without precious metals, temperatures in excess of 650°C must be obtained. At such high temperatures, elemental carbon will burn provided sufficient oxygen is present. However, diesel engines rarely if ever operate with such high exhaust temperatures. For example, exhaust temperatures on the HDE Federal Test Procedure cycle typically range from 100°C to 450°C. Precious metal CDPFs use platinum to oxidize NO in the exhaust to NO₂, which is capable of oxidizing carbon at temperatures as low as 250°C to 300°C.

Chapter III: Emissions Standards Feasibility

average four years of use covering more than 225,000 miles in applications ranging from city buses to garbage trucks to intercity trains, with some units accumulating more than 360,000 miles. When tested on the US Heavy-Duty Federal Test Procedure (HD FTP), they continued to demonstrate PM reductions in excess of 90 percent.

The experience gained in these field tests also helps to clarify the need for very low sulfur diesel fuel. In Sweden and some European city centers where below 10 ppm diesel fuel sulfur is readily available, more than 3,000 CDPFs have been introduced into retrofit applications without a single failure. This success on 10 ppm sulfur fuel is all the more impressive as some of these units have been in operation for more than six years. The field experience in areas where sulfur is capped at 50 ppm has been less definitive. In regions without extended periods of cold ambient conditions (such as the United Kingdom) field tests on 50 ppm cap sulfur fuel have been positive, with no reported durability issues. Of course, it should be mentioned that an HDDE equipped with a CDPF operating on 50 ppm sulfur would not meet the PM emission standards contained in this final rule, as discussed below. These good results in the UK are contrasted with field tests in Finland where colder winter conditions are sometimes encountered (similar to many northern regions of the United States). The testing in Finland revealed a failure rate of 10 percent (14 failures in the test program) when operated on fuel with a sulfur cap of 50 ppm. This 10 percent failure rate has been attributed to insufficient CDPF regeneration due to fuel sulfur in combination with low ambient temperatures.⁵ Other possible reasons for the high failure rate in Finland when contrasted with the Swedish experience appear to be unlikely. The Finnish and Swedish fleets were substantially similar, with both fleets consisting of transit buses powered by Volvo and Scania engines in the 10 to 11 liter range. Further, the buses were operated in city areas and none of the vehicles were operated in northern extremes such as north of the Arctic Circle.⁶ Given that the fleets in Sweden and Finland were substantially similar, and given that ambient conditions in Sweden are expected to be similar to those in Finland, we believe that the increased failure rates noted here are due to the higher fuel sulfur level in a 50 ppm cap fuel versus a 10 ppm cap fuel.^d Testing on an even higher fuel sulfur level of 200 ppm was conducted in Denmark on a fleet of 9 vehicles. In less than six months, all of the vehicles in the Danish fleet had failed due to plugging of the CDPFs.⁷ We believe that this real world testing clearly indicates that increasing diesel fuel sulfur levels limit CDPF regeneration, leading to plugging of the CDPF even at fuel sulfur levels as low as 50 ppm.

^d The average temperature in Helsinki, Finland, for the month of January is 21°F. The average temperature in Stockholm, Sweden, for the month of January is 26°F. The average temperature at the University of Michigan in Ann Arbor, Michigan, for the month of January is 24°F. The temperatures reported here are from www.worldclimate.com based upon the Global Historical Climatology Network (GHCN) produced jointly by the National Climatic Data Center and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory (ORNL).

Another program evaluating CDPFs in the field is the ARCO Emission Control Diesel (EC-D) program.^e In that program, a one-year technology validation is being run to evaluate EC-D and CDPFs using diesel vehicles operating in southern California. The fuel's performance, impact on engine durability and vehicle performance, and emission characteristics are being evaluated in several fleets in various applications. The program is still ongoing, but interim results have been made available.⁸ These interim results have shown that vehicles retrofitted with CDPFs and fueled with EC-D (7.4 ppm sulfur) emitted 91 percent to 99 percent less PM compared to the vehicles fueled with California diesel fuel (121 ppm sulfur) having no exhaust filter equipment. Further, the test vehicles equipped with the CDPFs and fueled with EC-D have operated reliably during the program start-up period and no significant maintenance issues have been reported for the school bus, tanker truck and grocery truck fleets that have been operating for over six months (approximately 50,000 miles).⁹

From these results, we can further conclude that lighter applications (such as large pick-up trucks and other light- and medium-heavy-duty applications), having lower exhaust temperatures than heavier applications, may experience similar failure rates even in more temperate climates and would, therefore, need lower sulfur fuel even in the United Kingdom. These results are understood to be due to the effect of sulfur on the CDPF's ability to create sufficient NO₂ to carry out proper filter regeneration. Without the NO₂, the CDPF continues to trap PM at high efficiency, but it is unable to oxidize, or regenerate, the trapped PM. The possible result is a plugged CDPF.

Much development effort is underway worldwide to bring PM exhaust emission control devices to market. One of the drivers is the Euro IV PM standard set to become effective in 2005.^f This standard sets a PM emission target that forces CDPF usage. In anticipation of the 2005 introduction date, field testing is already underway in several countries with CDPFs. We believe the experience gained in Europe with these technologies will coincide well with the 2007 standards contained in this final rule. The timing of the new standards harmonizes the heavy-duty highway PM technologies with those expected to be used to meet the light-duty highway Tier 2 standards. With this level of development already under way, we are confident that the PM standard will be met provided low sulfur fuel is made available.

The data currently available show that CDPFs can provide significant reductions in PM, and are capable of meeting a standard of 0.01 g/bhp-hr PM. CDPFs with precious metal catalysts, in conjunction with low sulfur fuel, have been shown to be more than 90 percent

^e EC-D is a diesel fuel developed recently by ARCO (Atlantic Richfield Company) from typical crude oil using a conventional refining process and having a fuel sulfur content less than 15 ppm.

^f The Euro IV standards are 2.6 g/hp-hr NO_x and 0.015 g/hp-hr PM over the European Stationary Cycle and European Transient Cycle.

efficient over the FTP and across the NTE zone.¹⁰ Figure III.A-1^g shows representative HD FTP CDPF efficiencies with fuel sulfur levels near 15 ppm.^{11 12 13 14} Since the total PM removal efficiency of the CDPF is roughly linear with fuel sulfur (as shown in the DECSE program results¹⁵), it can be seen from Figure III.A-1 that even at the 15 ppm sulfur cap, current CDPFs can produce greater than 90 percent trapping efficiency over the HD FTP. Based on the current FTP standard of 0.10 g/bhp-hr, these CDPFs will easily achieve the FTP 0.01 g/bhp-hr PM standard contained in today's final rule.

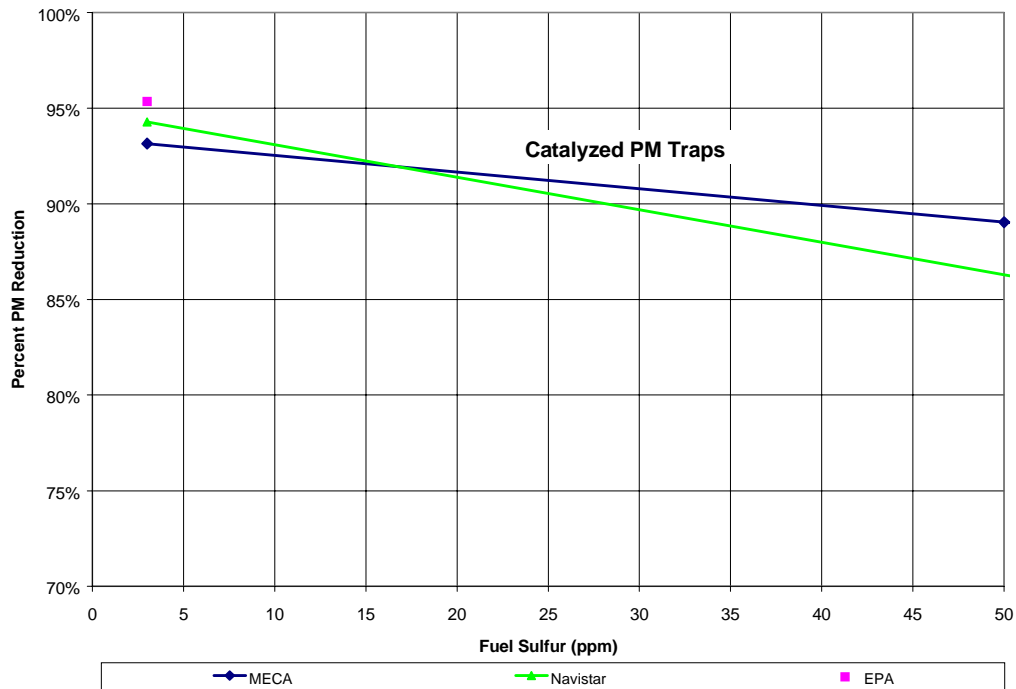


Figure III.A-1. HD CDPF PM Removal Efficiency Over the Federal Test Procedure

As part of the EPA National Vehicle and Fuel Emissions Laboratory (NVFEL) test program to evaluate CDPFs and NOx adsorbers, we performed CDPF testing over the hot-start HDDE FTP. This testing included CDPF evaluation with three ppm sulfur fuel, which produced greater than a 95 percent reduction in PM, with a post-CDPF emission rate of 0.004 g/bhp-hr PM.¹⁶ In addition, we performed testing of a complete system which included CDPFs, NOx adsorbers, and a clean-up diesel oxidation catalyst, which also produced on average greater than a 95 percent reduction during triplicate hot-start HDDE FTP testing, with an average post-CDPF

^g Figure III.A-1 includes a Navistar data point at 200 ppm sulfur and 61 percent PM reduction; this data point does not appear in the figure so that the data from 0 ppm sulfur to 50 ppm sulfur can be more easily viewed.

emission rate of 0.002 g/bhp-hr PM (with a 95 percent confidence interval of ± 0.001 g/bhp-hr), using six ppm sulfur fuel (additional discussion of this NVFEL test program can be found in section III.A.3.b of this RIA, as well as in the docket for this final rule).^h As indicated by Figure III.A-1, when typical particulate sulfate conversion rates for the HDDE FTP are considered, the EPA NVFEL test program would be projected to produce greater than a 90 percent PM reduction at a fuel sulfur level of 15 ppm.

The engine operating conditions have little impact on the particulate trapping efficiency of carbon particles by CDPFs, so the greater than 90 percent efficiency for elemental carbon particulate matter will apply to engine operation within the NTE zone, as well as the test modes which comprise the SET. This is supported by a study by Johnson Matthey which showed greater than 95 percent reduction in elemental carbon PM over a broad range of operating modes.¹⁷ This same paper also shows large reductions in the soluble organic fraction of the PM across the engine operating map. However, engine operation will affect the CDPF regeneration and oxidation of SO₂ to sulfate PM (i.e., “sulfate-make”). Sulfate-make will reduce the measured PM removal efficiency at some NTE operating conditions and supplemental steady-state modes, even at the 15 ppm fuel sulfur cap. Figure III.A-2 shows PM removal efficiency as a function of fuel sulfur for a CDPF when tested over the SET.¹⁸ From the graph, it can be seen that fuel sulfur level has a stronger effect on PM removal efficiency over the SET than over the HD FTP. This increased sensitivity to fuel sulfur is caused by the higher temperatures that are found at some of the steady-state modes. High exhaust temperatures promote the oxidation of SO₂ to SO₃ (which then combines with water in the exhaust, forming a hydrated sulfate) across the precious metals found in CDPFs. The sulfate emissions condense in the atmosphere (as well as in the CFR mandated dilution tunnel used for PM testing) forming PM. Figure III-A-2 shows PM reductions of 85 percent or greater are achievable with 15 ppm sulfur fuel. Engine-out PM emission rates over the SET test are typically 50 percent or less of the FTP PM emission rates, primarily because carbonaceous PM formation is greater under transient engine operation as compared to steady-state operation. For example, model year 2000 certification data for a number of HDDE families shows SET PM emission rates between 0.02 and 0.05 g/bhp-hr.¹⁹ Therefore, an 85 percent reduction in PM over the SET test is sufficient to comply with the 2007 SET PM standard contained in this final rule.

^h The NVFEL emission measurement test equipment used to evaluate the performance of a HDDE equipped only with a CDPF (no NO_x adsorbers) utilized PM sample equipment and procedures consistent with the existing 40 CFR part 86, subpart N provisions (including dual 70 mm filters). The NVFEL test equipment used to evaluate the performance of a complete system (CDPFs, NO_x adsorbers, clean-up DOC) utilized PM sample equipment and techniques consistent with the new PM measurement regulations contained in this rule, including a single, high efficiency 47 mm filter.

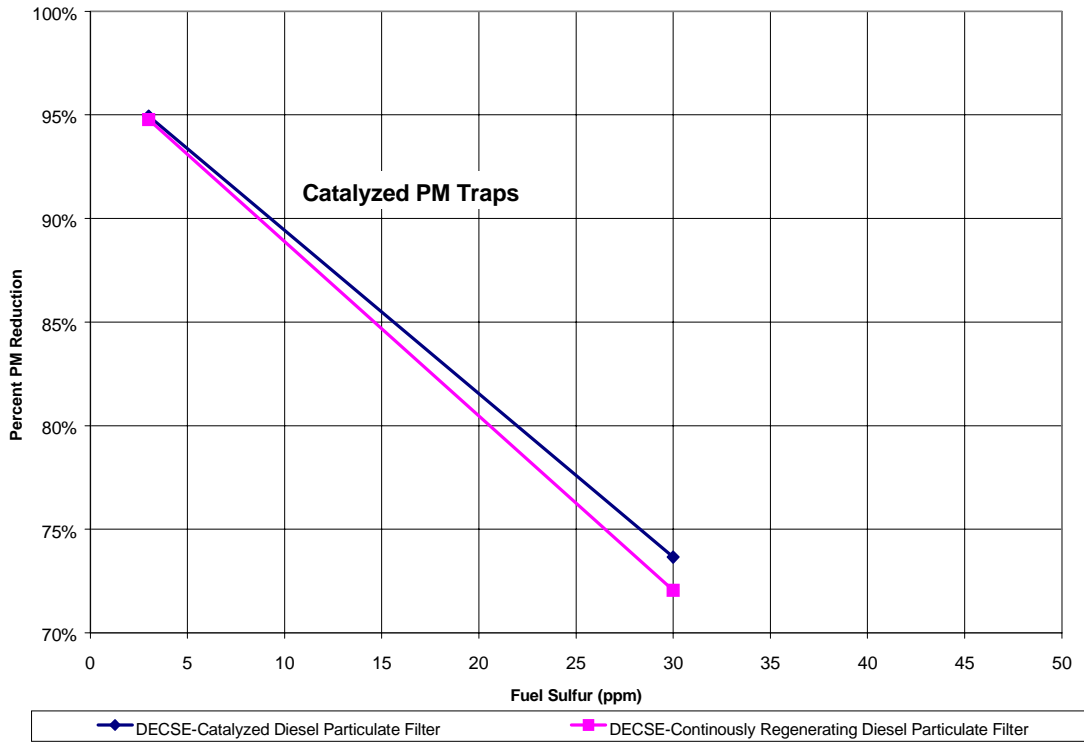


Figure III.A-2. HD PM Removal Efficiency for a CDPF Over the Supplemental Emission Test (SET)

Nonetheless, as shown in Table III.A-1, a HDDE equipped with CDPFs available today is capable of meeting the SET standard (equal to 1.0 x FTP standard, or 0.01 g/bhp-hr) with 15 ppm fuel. Table III.A-1 shows data from the Diesel Emission Control Sulfur Effects (DECSE) test program, a program conducted by the US Department of Energy in cooperation with industry to provide insight into the relationship between advanced emission control technologies and diesel fuel sulfur levels. Interim report number four of this program gives the total PM emissions from a heavy-duty diesel engine operated with a CDPF on several different fuel sulfur levels. Table III.A-1 also shows interpolated points representing a straight line fit through the DECSE data illustrating the expected total PM emissions from a heavy-duty diesel engine on the SET at various fuel sulfur levels. As shown, the PM emissions at a 15 ppm sulfur level would be 0.009 g/bhp-hr, ten percent below the 0.01 g/bhp-hr standard set in this final rule, which demonstrates the feasibility of the standard at 15 ppm sulfur.

Table III.A-1. PM Emissions from a Heavy-Duty Diesel Engine at the Indicated Fuel Sulfur Levels

<i>Fuel Sulfur Level</i>	<i>Supplemental Steady State</i>	
	<i>Tailpipe PM [g/bhp-hr]</i>	<i>Relative to the Standard (%)</i>
3	0.003	-70
7*	0.006	-40
15*	0.009	-10
30	0.017	70
150	0.071	610

* The PM emissions at these sulfur levels are based on a straight-line fit to the DECSE program data;²⁰ PM emissions at other sulfur levels are actual DECSE data.

The NTE requirement, unlike the HD FTP or SET standard, is not a composite test (i.e., the 20 minute transient HD FTP cycle or the 13-steady-state SET modes). In fact, a number of the individual modes within the SET test fall within the NTE engine control zone. As discussed above, CDPFs are very efficient at capturing elemental carbon PM (>95 percent), but sulfate-make under certain operating conditions may exceed the FTP or SET standard, which is part of the reason the PM NTE standard is greater than the FTP and SET PM standards. In addition to the composite SET results, the DECSE test program also reported PM performance results at two individual steady-state modes, the peak-torque condition and a “road-load” condition. The peak-torque test mode produces very high exhaust gas temperature (and would therefore be representative of the highest sulfate particulate generating conditions) and the road-load condition is intended to be representative of a typical HD diesel engine line-haul cruise operation (75 percent load, Euro B speed). A linear fit of the DECSE PM emission results for the road-load and peak-torque conditions between the three ppm sulfur test fuel and the 30 ppm sulfur test fuel point shows that the two CDPFs which were tested produced an 88-94 percent or greater reduction at a linear interpolated sulfur level of seven ppm (near the expected in-use average) and an 83-90 percent reduction at a linear interpolated sulfur level of 15 ppm (capped level), for both test operating points. For both CDPFs, the road-load condition resulted in lower sulfate make and higher overall PM reduction than the peak-torque condition. Based on this information, under very high particulate sulfate formation conditions, at 15 ppm sulfur a CDPF can produce at least an 83 percent reduction, and at the expected refinery average sulfur level of seven ppm, when operated at very high sulfate conversion engine conditions a CDPF can produce at least an 88 percent reduction. It should be noted that a prolonged steady-state test condition at the peak-torque mode for a HDDE is representative of the highest exhaust gas temperature producing engine operating conditions. The DECSE testing conditions for these two steady-state points

prescribed a five minute warm-up and a 20 minute sample collection, for a total of 25 minutes of operation at peak-torque. The peak-torque test data described above could be considered representative of the worst case particulate sulfate generating conditions. The data show that even under these test conditions, an 83 percent reduction would be sufficient to comply with the NTE provisions, even considering PM sulfate make, when tested on 15 ppm sulfur fuel. Under the Phase 1 rule, a HDDE could emit PM emissions subject to the NTE requirements as high as 0.13 g/bhp-hr (1.25 x 0.10 g/bhp-hr). An 83 percent reduction from this engine would result in a PM emission rate of 0.022 g/bhp-hr, which would comply with the 2007 NTE PM standards contained in this final rule.ⁱ

Under the Phase 1 HDDE provisions (which includes the Phase 1 FTP standards and the 2007 NTE provisions as they apply to the Phase 1 FTP standards), emission “carve-out” zones of the NTE control zone were defined. These carve-out zones are areas within the defined NTE control zone which are excluded from meeting the NTE standards for specific emissions. The Phase 1 rule defined two types of carve-out zones, one which applied to all regulated emissions (gaseous emissions and PM), and one carve-out zone which only applied to PM. The PM only carve-out zone was specified to exclude low load, high speed engine operation from the NTE requirements. During these conditions, HDDEs not equipped with CDPFs can produce higher PM emission rates, and it was decided within the Phase 1 rule to exclude HDDEs from complying with the PM NTE requirements when operated within the defined PM carve-out zones. With the application of CDPFs to HDDEs, these PM only carve-out zones are not needed. As discussed previously, CDPFs are very effective at reducing engine-out PM. During the recent NVFEL test program which evaluated the effectiveness of diesel CDPFs on low sulfur diesel fuel, we included one steady-state test point which was within the Phase 1 rule’s PM carve-out zone. Specifically, the test point was 228 ft-lbs torque and 2,415 rpm (listed as Mode 6 in Figure III.A-6 of this Chapter), which places the test condition near the center of the Phase 1 rule’s PM carve-out zone for this engine. At this operating condition, one of the CDPFs reduced engine-out PM by more than 95 percent, from 0.068 g/bhp-hr to 0.003 g/bhp-hr, the second CDPF produced similar results. Based on the high PM reduction capability of CDPFs when operated on low sulfur diesel fuel, and their demonstrated ability to achieve >90 percent reductions when operated inside the Phase 1 PM carve-out zones, we have eliminated the PM-only carve-out zones from the NTE requirements.

ⁱ The PM NTE standard contained in this final rule is 1.5 x FTP standard, or 1.5 x 0.01 g/bhp-hr. 40 CFR 86.007-11(a)(4)(v) specifies that the rounding procedures in ASTM E29-90 should be applied to the NTE emission standard, therefore, the NTE standard is rounded to the same number of significant digits as the FTP standard, i.e., 1.5 x 0.01g/bhp-hr is rounded to 0.02 g/bhp-hr. An engine with a measured NTE PM emission rate of 0.022 g/bhp-hr would also be rounded using ASTM rounding provisions, and would be rounded to the same number of significant digits as the standard, so 0.022 g/bhp-hr would round to 0.02 g/bhp-hr, and would meet the NTE PM standard.

The NTE requirements apply not only during standard laboratory conditions, but also during the expanded ambient temperature, humidity, and altitude limits defined in the regulations. We believe the NTE PM standard is technologically feasible across this range of ambient conditions. As discussed above, CDPFs are mechanical filtration devices, and ambient temperature changes will have minimal effect on CDPF performance. Ambient altitude will also have minimal, if any, effects on CDPF filtration efficiencies, and ambient humidity should have no effect on CDPF performance. As discussed above, particulate sulfate make is sensitive to high exhaust gas temperatures, however, at sea-level conditions, the NTE requirements apply up to ambient temperatures which are only 14°F greater than standard test cell conditions (100°F under the NTE, versus 86°F for HD FTP laboratory conditions). At an altitude of 5,500 feet above sea-level, the NTE applies only up to an ambient temperature within the range of standard laboratory conditions (i.e., 86°F). These small or non-existent differences in ambient temperature should have little effect on the sulfate make of CDPFs, and as discussed above, even when tested under at an engine operating test mode representative of the highest particulate sulfate generating conditions (25 minutes at peak-torque operation) with 15 ppm sulfur diesel fuel, we predict the engine would comply with the PM NTE standard. Based on the available test data and the expected impact of the expanded, but constrained, ambient conditions under which engines must comply with the NTE, we conclude that the PM NTE standard is technologically feasible by 2007, provided low sulfur diesel fuel (<15 ppm) is available.

There may be a need to remove, clean, and reverse these CDPFs at regular intervals to remove ash build-up resulting from engine oil. Small amounts of oil can enter the exhaust via the combustion chamber (past the pistons rings and valve seals), and via the crankcase ventilation system. This can lead to ash build-up, primarily as a result of the metallic oil additives used to provide pH control. This pH control is necessary, in part, to neutralize sulfuric acid produced as a byproduct of burning fuel containing sulfur. However, with reduced fuel sulfur, these oil additives could be reduced, thereby reducing the rate of ash build-up and lengthening any potential cleaning intervals. It may also be possible to use oil additives that are less prone to ash formation to reduce the need for periodic maintenance to at least those specified in CFR 86.004-25 (100,000 miles or 3,000 hours for light heavy-duty vehicles, and 150,000 miles or 4,500 hours for medium- and heavy-duty engines). Periodic maintenance would consist of reversing the CDPF and/or washing it out with compressed air or water. Consequently, we conclude that CDPFs will be able to meet the required emission life with minimal maintenance.

b. Control of Ultra-Fine PM

CDPFs reduce PM by capturing and burning particles. Ninety percent of the PM mass resides in particle sizes that are less than 1000 nanometers (nm) in diameter, and half of these particles are less than 200 nm.^{21 22 23 24 25} Fortunately, CDPFs have very high particle capture efficiencies. PM less than 200 nm is captured efficiently by diffusion onto surfaces within the CDPF walls. Larger particles are captured primarily by inertial impaction onto surfaces due to the

tortuous path that exhaust gas must take to pass through the porous CDPF walls. Capture efficiency for elemental carbon (soot) and metallic ash is nearly 100 percent; therefore, significant PM can only form downstream of the CDPF. Volatile PM forms from sulfate or organic vapors via nucleation, condensation, and/or adsorption during initial dilution of raw exhaust into the atmosphere. Kleeman, et al., and Kittelson, et al., independently demonstrated that these volatile particles reside in the ultra-fine PM range (i.e., <100 nm range).^{26 27} Thus ultra-fine PM is comprised primarily of semi-volatile PM. The organic portion of semi-volatile, ultra-fine PM can be controlled via oxidation over a PGM catalyst. The sulfate portion of semi-volatile, ultra-fine PM can be reduced by eliminating sulfur from the fuel. Furthermore, the work of Kittelson et al. suggests that reducing sulfate PM in this manner will reduce the number of nucleation sites available for the nucleation of ultra-fine organic PM, forcing more of the organic material to adsorb onto the much larger soot agglomerates and thus reducing the number of ultra-fine organic particles.

Modern CDPFs have been shown to be very effective at reducing PM mass. In addition, recent data shows that they are also very effective at reducing the overall number of emitted particles when operated on low sulfur fuel. Hawker, et. al., found that a modern CDPF reduced particle count by over 95 percent, including some of the smallest measurable particles (< 50 nm), at most of the tested conditions. The lowest observed efficiency in reducing particle number was 86 percent. No generation of particles by the CDPF was observed under any tested conditions.²⁸ Kittelson, et al., confirmed that ultra-fine particles can be reduced by a factor of ten by oxidizing volatile organics, and by an additional factor of ten by reducing sulfur in the fuel. CDPFs efficiently oxidize nearly all of the volatile organic PM precursors, and elimination of as much fuel sulfur as possible will substantially reduce the number of ultra-fine PM emitted from diesel engines. The combination of CDPFs with low sulfur fuel is expected to result in very large reductions in both PM mass and the number of ultra-fine particles.

3. Meeting the NOx Standard

NOx emissions from gasoline powered vehicles are controlled to extremely low levels through the use of the three-way catalyst technology first introduced in the 1970s. Historically, reduction of NOx emissions in the oxygen-rich environment typical of diesel exhaust has been significantly more difficult because known catalytic NOx reduction mechanisms like the gasoline three-way catalyst work only when the oxygen content of the exhaust is very low. Nevertheless, significant progress has been made in developing catalytic emission control technologies that reduce the NOx to form harmless oxygen and nitrogen in the oxygen rich (lean burn) exhaust environment typical of diesel engines. These devices are the lean NOx catalyst, the NOx adsorber, selective catalytic reduction (SCR), and non-thermal plasma.

a. Lean NOx Catalysts

Lean NOx catalysts have been under development for some time, and two methods have been developed for using a lean NOx catalyst depending on the level of NOx reduction desired though neither method can produce more than a 30 percent NOx reduction. The “active” lean NOx catalyst injects a reductant that serves to reduce NOx to N₂ and O₂ (typically diesel fuel is used as the reductant). The reductant is introduced upstream of, or into, the catalyst. The presence of the reductant provides locally oxygen poor conditions which allows the NOx emissions to be reduced by the catalyst.

The lean NOx catalyst washcoat incorporates a zeolite catalyst that acts to adsorb hydrocarbons from the exhaust stream. Once adsorbed on the zeolite, the hydrocarbons will oxidize and create a locally oxygen poor region that is more conducive to reducing NOx. To promote hydrocarbon oxidation at lower temperatures, the washcoat can incorporate platinum or other precious metals. The platinum also helps to eliminate the emission of unburned hydrocarbons that can occur if too much reductant is injected, referred to as “hydrocarbon slip.” With platinum, the NOx conversion can take place at the low exhaust temperatures that are typical of diesel engines. However, the presence of the precious metals can lead to production of sulfate PM, as already discussed for PM control technologies.

Active lean NOx catalysts have been shown to provide up to 30 percent NOx reduction under limited steady-state conditions. However, this NOx control is achieved with a fuel economy penalty upwards of 7 percent due to the need to inject fuel into the exhaust stream.²⁹ NOx reductions over the HD transient FTP are only on the order of 12 percent due to excursions outside the optimum NOx reduction efficiency temperature range for these devices.³⁰ Consequently, the active lean NOx catalyst does not appear to be capable of enabling the significantly lower NOx emissions required by the NOx standard.

The “passive” lean NOx catalyst uses no reductant injection. Therefore, the passive lean NOx catalyst is even more limited in its ability to reduce NOx because the exhaust gases normally contain very few hydrocarbons. For that reason, today’s passive lean NOx catalyst is capable of best steady state NOx reductions of less than 10 percent. Neither approach to lean NOx catalysis listed here can provide the significant NOx reductions required to satisfy the air quality needs discussed in chapter II.

b. NOx Adsorbers

NOx emissions from gasoline powered vehicles are controlled to extremely low levels through the use of the three-way catalyst technology first introduced in the 1970s. Today, an advancement upon this well developed three-way catalyst technology, the NOx adsorber, has shown that it too can make possible extremely low NOx emissions from lean burn engines such

as diesel engines. The potential of the NO_x adsorber catalyst is limited only by its need for careful integration with the total vehicle system (as was done for three-way catalyst equipped passenger cars in the 1980s and 1990s) and by poisoning of the catalyst from sulfur in the fuel. The following subsections describe the function, design and technical challenges remaining for application of the NO_x adsorber catalyst to heavy-duty diesel vehicles.

i. How do NO_x Adsorbers Work?

The NO_x adsorber catalyst is a further development of the three-way catalyst technology developed for gasoline powered vehicles more than twenty years ago. The NO_x adsorber enhances the three-way catalyst function through the addition of storage materials on the catalyst surface which can adsorb NO_x under oxygen rich conditions. This enhancement means that a NO_x adsorber can allow for control of NO_x emissions under lean burn (oxygen rich) operating conditions typical of diesel engines.

Three-way catalysts reduce NO_x emissions as well as HC and CO emissions (hence the name three-way) by promoting oxidation of HC and CO to water and CO₂ using the oxidation potential of the NO_x pollutant and in the process reducing the NO_x emissions to atomic nitrogen, N₂. Said another way, three-way catalysts work with exhaust conditions where the net oxidizing and reducing chemistry of the exhaust is approximately equal, allowing the catalyst to promote complete oxidation/reduction reactions to the desired exhaust components, carbon dioxide (CO₂), water (H₂O) and nitrogen (N₂). The oxidizing potential in the exhaust comes from NO_x emissions and some oxygen (O₂) which is not consumed during combustion. The reducing potential in the exhaust comes from HC and CO emissions, which represent products of incomplete combustion. Operation of the engine to ensure that the oxidizing and reducing potential of the combustion and exhaust conditions is precisely balanced is referred to as stoichiometric engine operation.

If the exhaust chemistry varies from stoichiometric conditions emission control is decreased. If the exhaust chemistry is net “fuel rich,” meaning there is an excess of HC and CO emissions in comparison to the oxidation potential of the NO_x and O₂ present in the exhaust, the excess HC and CO pollutants are emitted from the vehicle. Conversely, if the exhaust chemistry is net “oxygen rich” (lean burn), meaning there is an excess of NO_x and O₂ in comparison to the reducing potential of the HC and CO present in the exhaust, the excess NO_x pollutants are emitted from the vehicle. It is this oxygen rich operating condition that typifies diesel engine operation. Because of this, diesel engines equipped with three-way catalysts (or simpler oxidation catalysts) have very low HC and CO emissions while NO_x (and O₂) emissions remain almost unchanged from the high engine out levels. For this reason, when diesel engines are equipped with catalysts (diesel oxidation catalysts, or DOCs) they have HC and CO emissions that are typically lower, but have NO_x emissions that are an order of magnitude higher, than for gasoline engines equipped with three-way catalysts.

The NO_x adsorber catalyst works to overcome this situation by storing NO_x emissions when the exhaust conditions are oxygen rich. Unfortunately the storage capacity of the NO_x adsorber is limited, requiring that the stored NO_x be periodically purged from the storage component. If the exhaust chemistry is controlled such that when the stored NO_x emissions are released the net exhaust chemistry is at stoichiometric or net fuel rich conditions, then the three-way catalyst portion of the catalyst can reduce the NO_x emissions in the same way as for a gasoline three-way catalyst equipped engine. Simply put, the NO_x adsorber works to control NO_x emissions by storing NO_x on the catalyst surface under lean burn conditions typical of diesel engines and then by reducing the NO_x emissions with a three-way catalyst function by periodically operating under stoichiometric or fuel rich conditions.

The NO_x storage process can be further broken down into two steps. First the NO in the exhaust is oxidized to NO₂ across an oxidation promoting catalyst, typically platinum. Then the NO₂ is further oxidized and stored on the surface of the catalyst as a metallic nitrate (MNO₃). The storage components are typically alkali or alkaline earth metals that can form stable metallic nitrates. The most common storage component is barium carbonate (BaCO₃) which can store NO₂ as barium nitrate (Ba(NO₃)₂) while releasing CO₂. In order for the NO_x storage function to work, the NO_x must be oxidized to NO₂ prior to storage and a storage site must be available (the device cannot be “full”). During this oxygen rich portion of operation, NO_x is stored while HC and CO emissions are oxidized across the three-way catalyst components by oxygen in the exhaust. This can result in near zero emissions of NO_x, HCs, and CO under the net oxygen rich operating conditions typical of diesel engines.

The NO_x adsorber releases and reduces NO_x emissions under fuel rich operating conditions through a similar two step process, referred to here as NO_x adsorber regeneration. The metallic nitrate becomes unstable under net fuel rich operating conditions, decomposing and releasing the stored NO_x. Then the NO_x is reduced by reducing agents in the exhaust (CO and HCs) across a three-way catalyst system, typically containing platinum and rhodium. Typically this NO_x regeneration step occurs at a significantly faster rate than the period of lean NO_x storage such that the fuel rich operation constitutes only a small fraction of the total operating time. Since this release and reduction step, NO_x adsorber regeneration, occurs under net fuel rich operating conditions, NO_x emissions can be almost completely eliminated. But for some of the HC and CO emissions, “slip”(failure to remove all of the HC and CO) may occur during this process. The HC and CO slip can be controlled with a downstream “clean-up” catalyst that promotes their oxidation or potentially by controlling the exhaust constituents such that the excess amount of the HC and CO pollutants at the fuel rich operating condition is as low as possible, that is, as close to stoichiometric conditions as possible.

The difference between stoichiometric three-way catalyst function and the newly developed NO_x adsorber technology can be summarized as follows. Stoichiometric three-way catalysts work to reduce NO_x, HCs and CO by maintaining a careful balance between oxidizing

(NO_x and O₂) and reducing (HCs and CO) constituents and then promoting their mutual destruction across the catalyst on a continuous basis. The newly developed NO_x adsorber technology works to reduce the pollutants by balancing the oxidation and reduction chemistry on a discontinuous basis, alternating between net oxygen rich and net fuel rich operation in order to control the pollutants. This approach allows lean-burn engines (oxygen rich operating), like diesel engines, to operate under their normal operating mode most of the time, provided that they can periodically switch and operate such that the exhaust conditions are net fuel rich for brief periods. If the engine/emission control system can be made to operate in this manner, NO_x adsorbers offer the potential to employ the highly effective three-way catalyst chemistry to lean burn engines.

ii. *Where are NO_x Adsorbers used Today?*

NO_x adsorber catalysts were first introduced in the power generation market less than five years ago. Since then, NO_x adsorber systems in stationary source applications have enjoyed considerable success. In 1997, the South Coast Air Quality Management District of California determined that a NO_x adsorber system provided the “Best Available Control Technology” NO_x limit for gas turbine power systems.³¹ Average NO_x control for these power generation facilities is in excess of 92 percent.³² A NO_x adsorber catalyst applied to a natural gas fired powerplant has demonstrated better than 99 percent reliability for more than 21,000 hours of operation while controlling NO_x by more than 90 percent.³³ The experience with NO_x adsorbers in these stationary power applications shows that NO_x adsorbers can be highly effective for controlling NO_x emissions for extended periods of operation with high reliability.

The NO_x adsorber’s ability to control NO_x under oxygen rich (fuel lean) operating conditions has lead industry to begin applying NO_x adsorber technology to lean burn engines in mobile source applications. NO_x adsorber catalysts have been developed and are now in production for lean burn gasoline vehicles in Japan, including several vehicle models sold by Toyota Motor Corporation.^j The 2000 model year saw the first U.S. application of this technology with the introduction of the Honda Insight, certified to the California LEV-I ULEV category standard. These lean burn gasoline applications are of particular interest because they are similar to diesel vehicle applications in terms of lean NO_x storage and the need for periodic NO_x regeneration under transient driving conditions. The fact that they have been successfully applied to these mobile source applications shows clearly that NO_x adsorbers can work under transient conditions provided that engineering solutions can be found to periodically cause normally lean-burn exhaust conditions to operate in a rich regeneration mode.

^j Toyota requires that their lean burn gasoline engines equipped with NO_x adsorbers are fueled on premium gasoline in Japan, which has an average sulfur content of six ppm.

iii. *Can NOx Adsorbers be applied to Diesel Engines?*

NOx adsorbers work to control NOx emissions by storing the NOx pollutants on the catalyst surface during oxygen rich engine operation (lean burn engine operation) and then by periodically releasing and reducing the NOx emissions under fuel rich exhaust conditions. This approach to controlling NOx emissions can work for a diesel engine provided that the engine and emission control system can be designed to work in concert, with relatively long periods of oxygen rich operation (typical diesel engine operation) followed by brief periods of fuel rich exhaust operation. The ability to control the NOx emissions in this manner is the production basis for lean burn NOx emission control in stationary power systems and for lean burn gasoline engines. As outlined below we believe that there are several approaches to accomplish the required periodic operation on a diesel engine.

(a) *With In-Cylinder Control Systems*

The most frequently mentioned approach for controlling the exhaust chemistry of a diesel engine is through in-cylinder changes to the combustion process. This approach roughly mimics the way in which lean-burn gasoline engines function with NOx adsorbers. That is the engine itself changes in operation periodically between “normal” lean burn (oxygen rich) combustion and stoichiometric or even fuel rich combustion in order to promote NOx control with the NOx adsorber catalyst. For diesel engines this approach typically requires the use of common rail fuel systems which allow for multiple fuel injection events along with an air handling system which includes exhaust gas recirculation (EGR).

The normal lean burn engine operation can last from as little time as 15 seconds to more than three minutes as the exhaust NOx emissions are stored on the surface of the NOx adsorber catalyst. The period of fuel lean, oxygen rich, operation is determined by the NOx emission rate from the engine and the storage capacity of the NOx adsorber. Once the NOx adsorber catalyst is full (once an unacceptable amount of NOx is slipping through the catalyst without storage) the engine must switch to fuel rich operation in order to regenerate the NOx adsorber.

The engine typically changes to fuel rich operation by increasing the EGR rate, by throttling the fresh air intake, and by introducing an additional fuel injection event late in the combustion cycle. The increased EGR rate works to decrease the oxygen content of the intake air by displacing fresh air that has a high oxygen content with exhaust gases that have a much lower oxygen content. Intake air throttling further decreases the amount of fresh air in the intake gases again lowering the amount of oxygen entering the combustion chamber. The combination of these first two steps serves to lower the oxygen concentration in the combustion chamber, decreasing the amount of fuel required in order to reach a fuel rich condition. The fuel is metered then into the combustion chamber in two steps under this mode of operation. The first, or primary, injection event meters a precise amount of fuel in order to deliver the amount of

torque (energy) required by the operator demand (accelerator pedal input). The second injection event is designed to meter the amount of fuel necessary in order to achieve a net fuel rich operating condition. That is, the primary plus secondary injection events introduce an excess of fuel when compared to the amount of oxygen in the combustion chamber. The secondary injection event occurs very late in the combustion cycle so that no torque is derived from its introduction. This is necessary so that the switching between the normal lean burn operation and this periodic fuel rich operation is transparent to the user.

Additional ECM capability will be necessary to monitor the NO_x adsorber and determine when the NO_x regeneration events are necessary. This could be done in a variety of ways, though they fall into two general categories: predictive and reactive. The predictive method would estimate or measure the NO_x flow into the adsorber in conjunction with the predicted adsorber performance to determine when the adsorber is near capacity. Then, upon entering optimal engine operating conditions, a NO_x regeneration would be performed. This particular step is similar to an on-board diagnostic (OBD) algorithm waiting for proper conditions to perform a functionality check. During the NO_x regeneration, sensors would determine how accurately the predictive algorithm performed, and adjust it accordingly. The reactive method is envisioned to monitor NO_x downstream of the NO_x adsorber and, if NO_x slippage is detected, a regeneration event would be triggered. This method is dependent on good NO_x sensor technology. This method would also depend on the ability to regenerate under any given engine operating condition, since the algorithm would be reacting to indications that the adsorber had reached its NO_x storage capacity. In either case, we believe these algorithms are not far removed from those used today for other purposes. When used in combination with the sophisticated control systems that will be available, we expect that NO_x regeneration events can be seamlessly integrated into engine operation such that the driver may not be aware that the events are taking place.

Using this approach of periodic switching between normal lean burn operation and brief periods of fuel rich operation all accomplished within the combustion chamber of a diesel engine is one way in which an emission control system for a diesel engine can be optimized to work with the NO_x adsorber catalyst. This approach requires no new engine hardware beyond the air handling and advanced common rail fuel systems that many advanced diesel engines will have already applied in order to meet the Phase 1 EGR based NO_x standard. For this reason an in-cylinder approach is likely to appeal to engine manufacturers for product lines where initial purchase cost is the most important factor in determining engine purchases. A Department of Energy (DOE) research program has already demonstrated that this approach can work.³⁴

This in-cylinder approach is not without some drawbacks. The high EGR rates and very low oxygen content of the intake air supply during rich operation can lead to poor combustion quality, increased fuel consumption and increased PM formation. Since all of the exhaust gases must be made rich under this approach, the amount of fuel added from the secondary

injection event can be substantial leading to an even greater increase in fuel consumption. Further the secondary injection event which occurs very late in the combustion cycle has the potential to lead to dilution of the engine lubricating oil with diesel fuel. This can occur when the fuel injection spray “over-penetrates” and impinges on the cylinder walls. The fuel on the cylinder walls is “scraped” into the engine crankcase by the same piston ring technology that is designed to control oil consumption. Dilution of the lubricating oil can lead to increased engine wear rates. Fortunately the period of fuel rich operation is typically very brief in relation to the period of normal lean burn operation. As an example lean burn operation may have a one minute duration while the fuel rich operation can be as brief as two seconds. The fact that the fuel rich operation occurs for only brief periods helps to alleviate concerns about this operating mode. Further, the complete emission control system can be designed to address concerns about the very brief increase in PM emissions through the use of a CDPF.

(b) With External Control Systems

The in-cylinder approach to optimizing a diesel engine NO_x emission control system to work with a NO_x adsorber has several drawbacks which may make it a less desirable solution for heavy heavy-duty diesel engines which can have an extremely long engine life and for which fuel economy is a greater concern than initial purchase price. For these applications it would be desirable to develop a system which could function outside of the engine’s combustion system independent of engine operating mode. This would allow the diesel engine itself to continue to be designed for maximum durability and minimum fuel consumption while always operating in an oxygen rich environment as is typical of today’s diesel engines. This is precisely what is done today for NO_x adsorber systems applied to stationary power sources.

One approach to accomplish this goal is through the use of a so called “dual-bed” or “multiple-bed” NO_x adsorber catalyst system. Such a system is designed so that the exhaust flow can be partitioned and routed through two or more catalyst “beds” which operate in parallel. Multiple-bed NO_x adsorber catalysts restrict exhaust flow to part of the catalyst during its regeneration. By doing so, only a portion of the exhaust flow need be made rich, reducing dramatically the amount of oxygen needing to be depleted and thus the fuel required to be injected in order to generate a rich exhaust stream. One simple example of a multiple bed NO_x adsorber is the dual-bed system in Figure III.A-3. In this example, the top half of the adsorption catalyst system is regenerating under a low exhaust flow condition (exhaust control valve nearly closed), while the remainder of the exhaust flow is bypassed to a lower half of the system. A system of this type would have the following characteristics:

- Half of the system would operate with a major flow in an “adsorption mode”, where most of the exhaust is well lean of stoichiometric ($\lambda > 1$ or $\gg 1$, typical

diesel exhaust), NO is converted to NO₂ over a Pt-catalyst, and stored as a metallic nitrate within the NO_x adsorbent material.^k

- The other half of the system would have its exhaust flow restricted to just a small fraction (~5 percent) of the total flow and would operate in a regeneration mode.
 - While the flow is restricted for regeneration, a small quantity of fuel is sprayed into the regenerating exhaust flow at the beginning of the regeneration event.
 - The fuel is oxidized by the oxygen in the exhaust until sufficient oxygen is depleted for the stored NO_x to be released. This occurs at exhaust conditions of $\lambda \leq 1$.
 - At these conditions, NO_x can also be very efficiently reduced to N₂ and O₂ over a precious metal catalyst.
- At the completion of regeneration, the majority of the flow can then be reintroduced into the regenerated half of the system by opening the flow control valve.
- Simultaneously, flow is restricted to the other half of the system to allow it to regenerate.

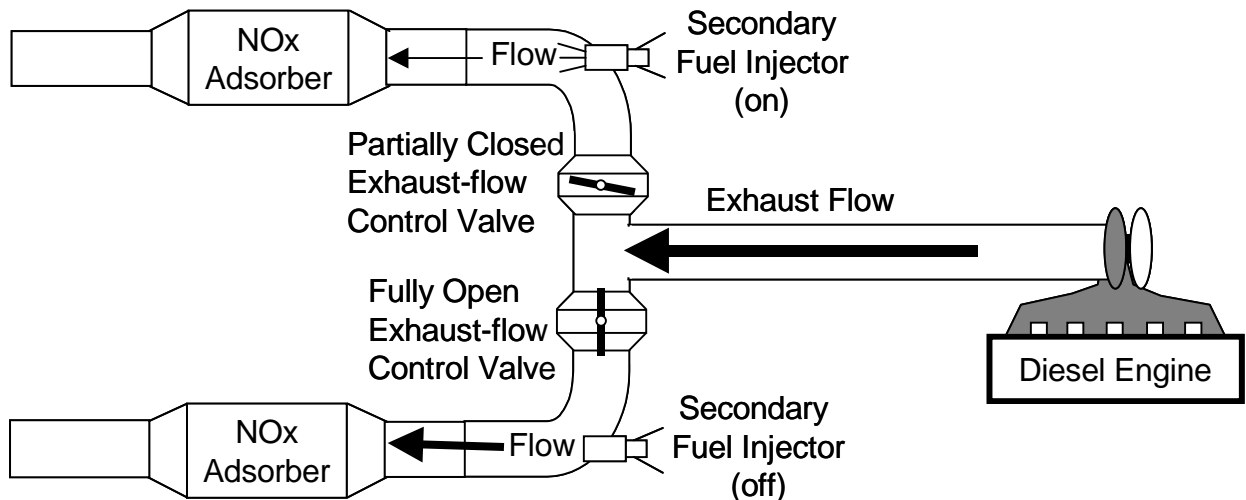


Figure III.A-3. Schematic Representation of the Operation of a Dual-Bed NO_x Adsorption Catalyst

^k A condition of $\lambda = 1$ means that there are precisely the needed quantity of reactants for complete reaction at equilibrium. $\lambda < 1$ means that there is insufficient oxygen, $\lambda > 1$ means that there is excess oxygen.

The primary advantage of such a system is to significantly reduce fuel consumption compared to single-bed approaches to NO_x adsorber catalysts. Since oxygen must be depleted from the exhaust during regeneration of the NO_x adsorber, depleting oxygen from a minor flow requires much less fuel than depleting oxygen from the entire exhaust as would be required with a single-bed NO_x adsorber approach. Control of the system is also somewhat less complicated due to the segregation of the exhaust control external to the engine. This avoids some of the issues highlighted above with a secondary injection event used for an in-cylinder approach. The disadvantage is the need for additional hardware and a somewhat more complicated exhaust system.

Although the schematic shows two separate systems, the diversion of exhaust flow can occur within a single catalyst housing, and with a single catalyst monolith. Toyota has already demonstrated flow-switching within a single device with their new combination CDPF/NO_x adsorber.³⁵ There may also be advantages to using more than one partition for the NO_x adsorber system, for example:

- Multiple bed NO_x adsorbers increase adsorption capacity by allowing more complete regeneration than is typically possible with a single bed.
- Use of multiple beds allows desulfation of one bed while normal NO_x adsorption and regeneration events occur in other beds.

The NO_x adsorber performance can be enhanced by incorporating a catalyzed diesel particulate filter (CDPF) into the system. A number of synergies exist between NO_x adsorber systems and CDPFs. Both systems rely on conversion of NO to NO₂ over a Pt catalyst for part of their functioning. Partial oxidation reforming of diesel fuel to hydrogen and CO over a Pt-catalyst has been demonstrated for fuel-cell applications. A similar reaction to reform the fuel upstream of the NO_x adsorber during regeneration would provide a more reactive reductant for desorption and reduction of NO_x. Heavier fuel hydrocarbons are known to inhibit NO_x reduction on the NO_x adsorption catalyst since competitive adsorption by hydrocarbons on the precious metal sites inhibits NO_x reduction during adsorber regeneration.³⁶ Partial oxidation of the secondary fuel injected into the exhaust during regeneration could lead to sooting of the fuel. Using a CDPF upstream of the NO_x adsorber, but downstream of the secondary fuel injection, allows partial oxidation of the fuel hydrocarbons to occur over the Pt catalyst on the surface of the CDPF. The wall-flow design of the CDPF efficiently captures any soot formed during partial oxidation of the fuel injected into the exhaust, preventing any increase in soot emissions. The partial oxidation reaction over the CDPF is exothermic, which could be used increase the rate of temperature rise for the NO_x adsorber catalyst after cold starts, similar to the use of light-off catalysts with cascade three-way catalyst systems.³⁷ The schematic in Figure III.A-4 shows the integrated dual-bed NO_x adsorber and CDPF system developed for testing at EPA-NVFEL, along with a potential second generation of this type of emission control system having an

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additional partition for NO_x adsorption/regeneration and further integration of the components. The use of a DOC for HC and H₂S control may be necessary downstream of the NO_x adsorbers partitions. The system tested at NVFEL is described in more detail in a memo to the docket for this final rule.³⁸

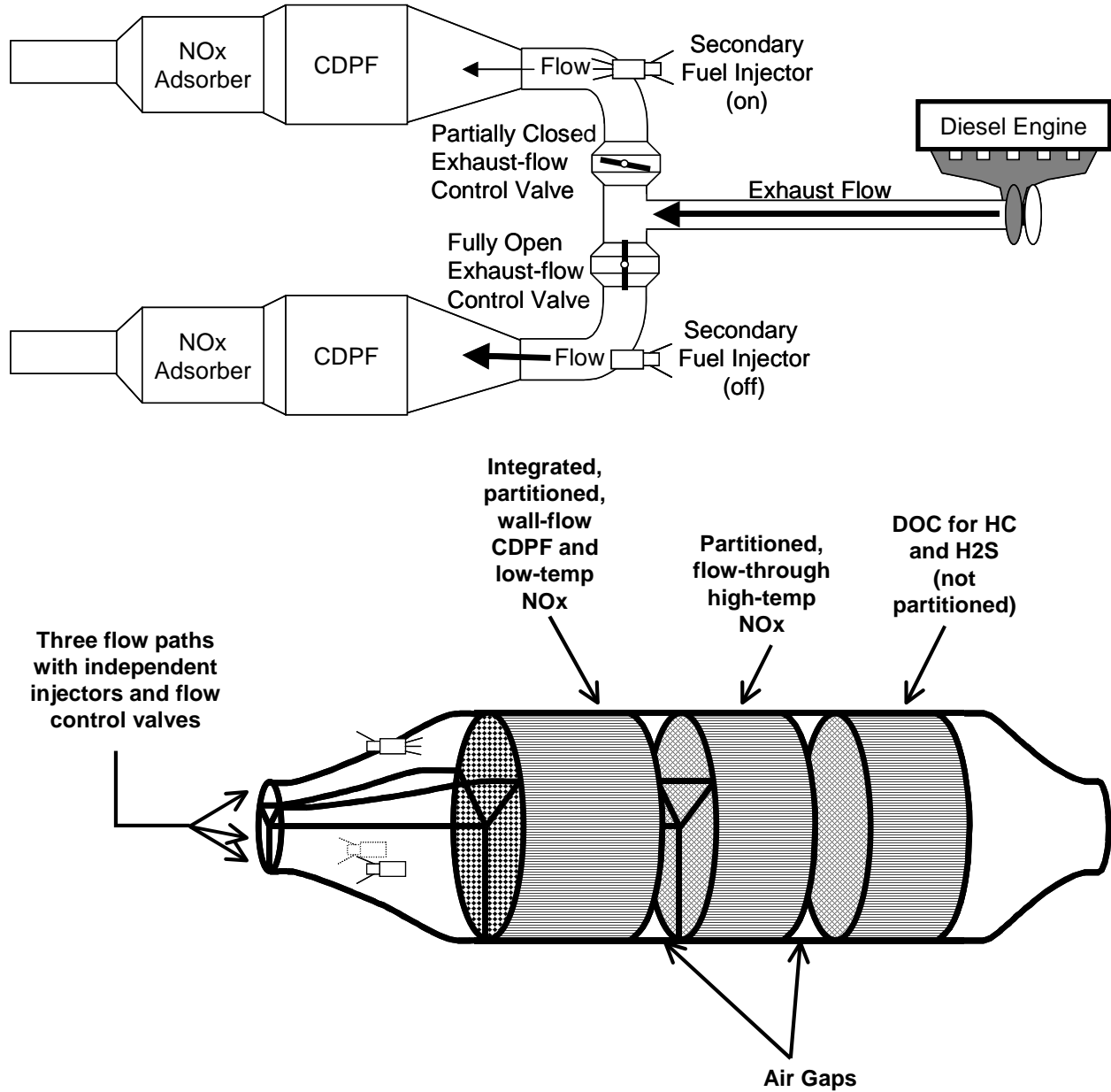


Figure III.A-4. A functional schematic representation of the PM and NOx exhaust emission control system tested at NVFEL shown together with one possible approach having the same functionality, but with further integration of components

A multiple-bed device of this type could be manufactured using a single, wall-flow monolith within a single housing with an internal valve for flow diversion. One possible configuration of such a system is shown in Figure III.A-4 above. Toyota has already demonstrated a similar concept, catalyst can with internal valving that uses a single wall-flow monolith. Components washcoated onto the surfaces of the wall-flow monolith of the Toyota system are used to provide oxidation catalysis for efficient PM regeneration, and also provide alkaline-metal adsorption sites for NO_x storage during lean operation. The internal valving is currently used by Toyota for flow reversal, and the device was originally configured for the NO_x adsorber function to regenerate as a single bed during full rich operation. A similar device could be reconfigured to allow diversion of the exhaust gases through alternating portions of the wall-flow monolith for a dual-bed approach. Integration of NO_x and PM control components into this sort of dual-bed system would:

- allow the low-fuel consumption benefits of a multiple-bed NO_x adsorber approach,
- provide a wall-flow CDPF for partial oxidation of the secondary fuel needed for regeneration
- reduce the mass of the entire system for improved performance
- reduce the size of the system for better integration of the system into applications with tight packaging constraints (as with some light- and medium-heavy-duty diesel engine applications)
- reduce the price of the system by allowing the use of a single monolith and housing instead of four or more separate devices.

iv. *How Efficient are Diesel NO_x Adsorbers?*

Research into applying the NO_x adsorber catalyst to diesel exhaust is only a few years old but benefits from the larger body of experience with stationary power sources and with lean burn gasoline systems. In simplest terms the question is how well does the NO_x adsorber store NO_x under normal lean burn diesel engine operation, and then how well does the control system perform the NO_x regeneration function. Both of these functions are affected by the temperature of the exhaust and of the catalyst surface. For this reason efficiency is often discussed as a function of exhaust temperature under steady-state conditions. This is the approach used in this section. The potential for both NO_x storage and reduction to operate at very high efficiencies can be seen through careful emission control system design as described below.

(a) At Storing NO_x Under Oxygen Rich (fuel lean) Conditions?

The NO_x storage function as described in section III.A.3.b.i., above, consists of oxidation of NO to NO₂ and then storage of the NO_x as a metallic nitrate on the catalyst surface. The effectiveness of the catalyst at accomplishing these tasks is dependent upon exhaust temperature,

catalyst temperature, precious metal dispersion, NO storage volume, and transport time (mass flow rates through the catalyst). Taken as a whole these factors determine how effective a NOx adsorber based control system can store NOx under lean burn diesel engine operation.

Catalyst and exhaust temperature are important because the rate at which the desirable chemical reactions occur is a function of the local temperature where the reaction occurs. The reaction rate for NO to NO₂ oxidation and for NOx storage increases with increasing temperature. Beginning at temperatures as low as 100°C NO oxidation to NO₂ can be promoted across a platinum catalyst at a rate high enough to allow for NOx storage to occur. Below 100°C the reaction can still occur (as it does in the atmosphere) however the reaction rate is so slow as to make NOx storage ineffective below this temperature in a mobile source application. At higher exhaust temperatures, above 400°C, two additional mechanisms affect the ability of the NOx adsorber to store NOx. First the NO to NO₂ reaction products are determined by an equilibrium reaction which favors NO rather than NO₂. That is across the oxidation catalyst, NO is oxidizing to form NO₂ and NO₂ is decaying to form NO at a rate which favors a larger fraction of the gas being NO rather than NO₂. As this is an equilibrium reaction when the NO₂ is removed from the gas stream by storage on the catalyst surface, the NOx gases quickly “re-equilibrate” forming more NO₂. This removal of NO₂ from the gas stream and the rapid oxidation of NO to NO₂ means that in spite of the NO₂ fraction of the NOx gases in the catalyst being low at elevated conditions (30 percent at 400°C) the storage of NOx can continue to occur with high efficiencies, near 100 percent.

Unfortunately the other limitation of high temperature operation is not so easily overcome. The metallic nitrates that are formed on the catalyst surface and that serve to store the NOx emissions under fuel lean operating conditions can become unstable at elevated temperatures. That is, the metallic nitrates thermally decompose releasing the stored NOx under lean operating conditions allowing the NOx to exit the exhaust system “untreated.” The temperature at which the storage metals begin to thermally release the stored NOx emissions varies dependent upon the storage metal or metals used, the relative ratio of the storage metals, and the washcoat design. Changes to catalyst formulations can change the upper temperature threshold for thermal NOx desorption by as much as 100°C.³⁹ Thermal stability is the primary factor determining the NOx control efficiency of the NOx adsorber at temperatures higher than 400-500°C.

(b) At Reducing NOx Under Fuel Rich Conditions?

The NOx adsorber catalyst releases stored NOx emissions under fuel rich operating conditions and then reduces the NOx over a three-way catalyst function. While the NOx storage function determines the NOx control efficiency during lean operation it is the NOx release and reduction function that determines the NOx control efficiency during NOx regeneration. Since NOx storage can approach near 100 percent effectiveness for much of the temperature range of

the diesel engine, the NO_x reduction function often determines the overall NO_x control efficiency.

NO_x release can occur under relatively cool exhaust temperatures even below 200°C for current NO_x adsorber formulations. Unfortunately the three-way NO_x reduction function is not operative at such cool exhaust temperatures. The lowest temperature at which a chemical reaction is promoted at a defined efficiency (often 50 percent) is referred to as the “light-off” temperature. The 80 percent light-off temperature for the three-way catalytic NO_x reduction function of current NO_x adsorbers is between 200°C and 250°C. Therefore, even though NO_x storage and release can occur at cooler temperatures, NO_x control is limited under steady-state conditions to temperatures greater than this light-off temperature.

Under transient operation however, NO_x control can be accomplished at temperatures below this NO_x reduction light-off temperature provided that the period of operation at the lower temperature is preceded by operation at higher temperatures and provided that the low temperature operation does not continue for an extended period. This NO_x control is possible due to two characteristics of the system specific to transient operation. First, NO_x control can be continued below the light-off temperature because storage can continue below that temperature. If the exhaust temperature again rises above the NO_x reduction light-off temperature before the NO_x adsorber storage function is full the NO_x reduction can then precede at high efficiency. Said another way, if the excursions to very low temperatures are brief enough, NO_x storage can precede under this mode of operation followed by NO_x reduction when the exhaust temperatures are above the light-off temperature. Although this sounds like a limited benefit because NO_x storage volume is limited, in fact it can be significant, because the NO_x emission rate from the engine is low at low temperatures. While the NO_x storage rate may be limited such that at high load conditions the lean NO_x storage period would be as short as 30 seconds, at the very low NO_x rates typical of low temperature operation (operation below the NO_x reduction light-off temperature) this storage period can increase dramatically. This is due to the NO_x mass flow rate from the engine changing by several orders of magnitude between idle conditions and full load conditions. The period of lean NO_x storage would be expected to increase in inverse proportion to the NO_x emission rate from the engine. Therefore the period of NO_x storage under light load conditions could likewise be expected to increase by orders of magnitude as well.

Transient operation can further allow for NO_x control below the NO_x reduction light-off temperature due to the thermal inertia of the emission control system itself. The thermal inertia of the emission control system can work to warm the exhaust gases to a local temperature high enough to promote the NO_x reduction reaction even though the inlet exhaust temperatures are below the light-off temperature for the catalyst. In testing at NVFEL (discussed below in section III.A.3.b.v.c) exhaust temperatures were above the NO_x reduction light-off temperature for testing at engine loads as low as 25 percent of full load. In as much as heavy-duty diesel engines are expected to operate under some load for most operating conditions, the exhaust temperature

will be expected to be above this threshold on average. Therefore the NO_x emission control system temperature is expected to be above the light-off temperature for almost all operation, even when the engine exhaust temperature drops below this level due to the thermal inertia of the exhaust control system.

The combination of these two effects was observed during testing of NO_x adsorbers at NVFEL especially with regards to NO_x control under idle conditions. It was observed that when idle conditions followed loaded operation, for example when cooling the engine down after a completing an emission test, that the NO_x emissions were effectively zero (below background levels) for extended periods of idle operation (for more than 10 minutes). Additionally it was discovered that the stored NO_x could be released and reduced in this operating mode even though the exhaust temperatures were well below 250°C provided that the regeneration event was triggered within the first 10 minutes of idle operation (before the catalyst temperature decreased significantly). However, if the idle mode was continued for extended periods (longer than 15 minutes) NO_x control eventually diminished. The loss of NO_x control at extended idle conditions appeared to be due to the inability to reduce the stored NO_x leading to high NO_x emissions during NO_x regeneration cycles.

NO_x control efficiency with the NO_x adsorber technology under steady-state operating conditions can be seen to be limited by the light-off temperature threshold of the three-way catalyst NO_x reduction function. Further a mechanism for extending control below this temperature is described for transient operation and is observed in testing of NO_x adsorber based catalyst systems.

(c) For Overall Diesel NO_x Control?

Overall NO_x adsorber efficiency reflects the composite effectiveness of the NO_x adsorber in storing, releasing and reducing NO_x over repeated lean/rich cycles. As detailed above, exhaust temperatures play a critical role in determining the relative effectiveness of each of these catalyst functions. These limits on the individual catalyst functions can explain the observed overall NO_x control efficiency of the NO_x adsorber, and can be used to guide future research to improve overall NO_x adsorber efficiency and the design of an integrated NO_x emission control system.

At low exhaust temperatures overall NO_x control is limited by the light-off temperature threshold of the three-way NO_x reduction function in the range from 200°C to 250°C. At high temperatures (above 400° to 500°C) overall NO_x control is limited by the thermal stability of the NO_x storage function. For exhaust temperatures between these two extremes NO_x control can occur at virtually 100 percent effectiveness.

The ability of the complete system including the engine and the emission control system to control NO_x emissions consistently well in excess of 90 percent is therefore dependent upon the careful management of temperatures within the system. Figure III.A-5 provides a pictorial representation of these constraints and indicates how well a diesel engine can match the capabilities of a NO_x adsorber based NO_x control system. The figure shows accumulated NO_x emission (grams) over the heavy-duty FTP test for both a light heavy-duty (LHD) and a heavy heavy-duty (HHD) engine. The engine-out NO_x emissions are shown as the dark bars on the graphs. The accumulated NO_x emissions shown here, divided by the integrated work over the test cycle gives a NO_x emission rate of 4 g/bhp-hr (the 1998 HD emission standard) for each of these engines. Also shown on the graph as a solid line is the steady-state NO_x conversion efficiency for a NO_x adsorber, MECA "B", used in testing at NVFEL (see section A.v.c below for more details on testing at NVFEL). The line has been annotated to show the constraint under low temperature operation (three-way catalyst light-off). The white bars on the graph represent an estimate of the tailpipe NO_x emissions that could be realized from the application of the NO_x adsorber based upon the steady-state efficiency curve for adsorber MECA "B". These estimated tailpipe emissions are highest in the temperature range below 250°C even though the engine out NO_x emissions are the lowest in this region. This is due to the light-off temperature threshold for the NO_x three-way reduction function.

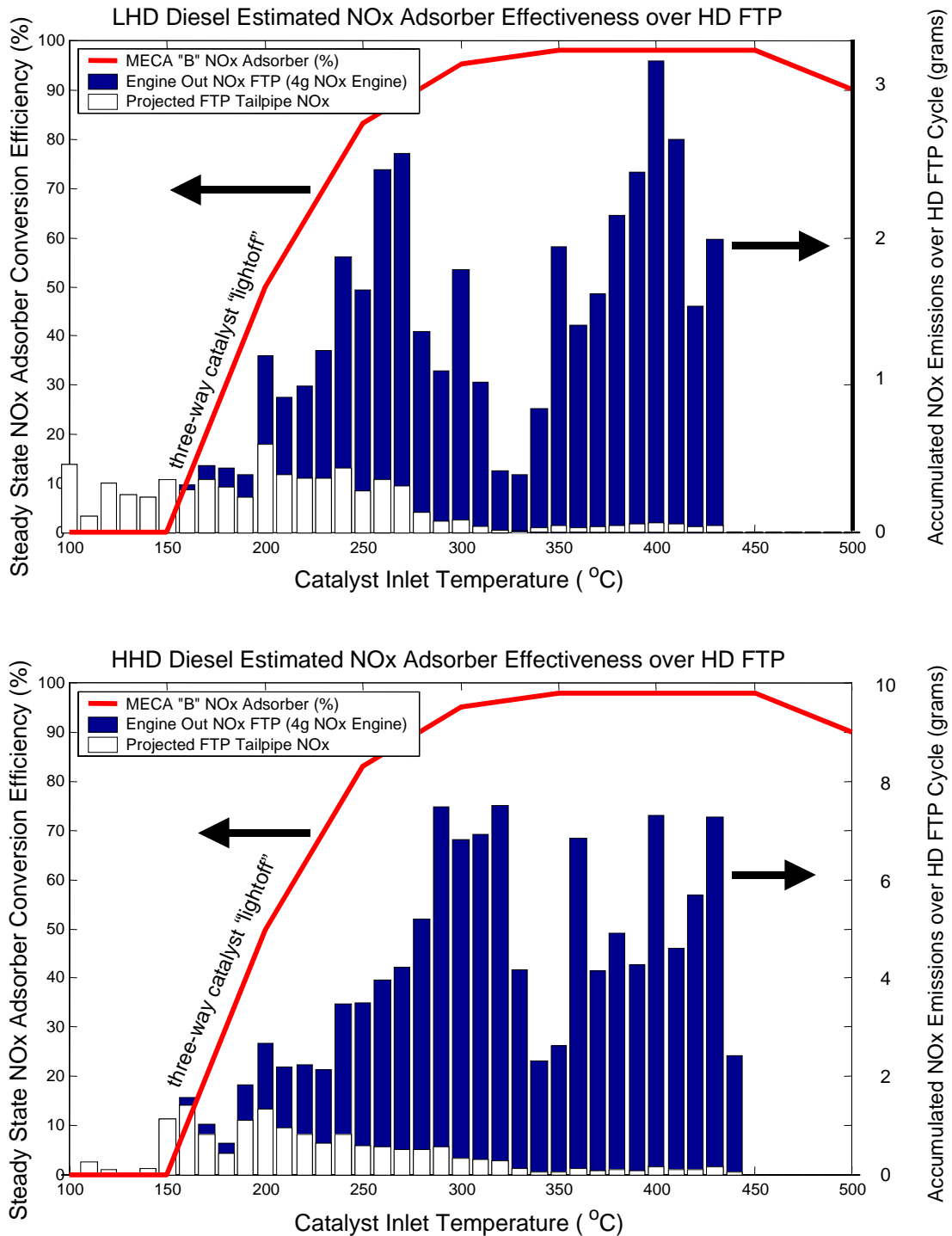


Figure III.A-5. NOx Adsorber Efficiency Characteristics versus Exhaust Temperature

Since the conversion efficiencies are based upon steady-state operation it is likely that the low temperature performance could be better than estimated here due to catalyst's ability to store the NO_x emissions at these low temperatures and then to reduce them when transient operation raises the exhaust temperatures above the three-way light-off temperature. This assertion provides one explanation for differences noted between this approximation to the FTP NO_x efficiency for the LHD engine shown in Figure III.A-5 above and actual NO_x adsorber efficiency demonstrated with this engine in the NVFEL test program. Based upon the figure above (using the steady-state conversion estimate) the NO_x adsorber catalyst should have provided less than an 84 percent reduction in NO_x emissions over the FTP. However testing at NVFEL (detailed in section III.A.v.c) has already demonstrated a 90 percent reduction in NO_x emissions with this same engine and catalyst pair without significant optimization of the system. Clearly then steady-state NO_x adsorber performance estimates can underestimate the real NO_x reductions realized in transient vehicle operation as typified by the HD FTP.

The tailpipe NO_x emissions are the lowest in the range from 250°C to 450°C, even though this is where the majority of the engine out NO_x emissions are created, because of the high overall NO_x reduction efficiency of the NO_x adsorber system under these conditions. At temperatures above 500°C the NO_x conversion efficiency of the NO_x adsorber can be seen to decrease. However since exhaust temperatures over the FTP for both of these engines remained below 450°C this loss of NO_x control at high temperatures did not affect the overall NO_x conversion efficiency. As detailed in section III.A.v.c below, this loss in NO_x efficiency at high temperatures is a more important consideration for the SET test where higher exhaust temperatures at some test points are possible.

Figure III.A-5 shows that the temperature window of a current technology NO_x adsorber catalyst is well matched to the exhaust temperature profiles of a light heavy-duty and a heavy heavy-duty diesel engine operated over the heavy-duty FTP driving cycle. Testing at NVFEL on the same light heavy-duty engine operated over the SET, shows that even for extended high load operation, as typified by the 100 percent load test points in the procedure, NO_x conversion efficiencies remained near or above 90 percent (See discussion of the NVFEL test program in section III.A.3.b.v.c, below).

The discussion above makes it clear that when the engine and NO_x adsorber based emission control system are well matched that NO_x reductions can be far in excess of 90 percent. Conversely it can be inferred that if exhaust temperatures are well in excess of 500°C or well below 200°C for significant periods of engine operation then NO_x control efficiency may be reduced. Fortunately the temperature window for NO_x adsorber and diesel engines are inherently well matched as shown in Figure III.A-5. Researchers are known to be developing and testing new NO_x adsorber formulations designed to increase the high temperature stability of the NO_x adsorber.⁴⁰ The unique characteristics of the NO_x adsorber will mean that integrated total

systems approaches will be needed in order to ensure compliance with the NO_x standards under a wide range of conditions.

v. *Progress in NO_x Adsorber Development for Diesel Engines*

(a) Industry Progress

The rapid development of the NO_x adsorber technology is not limited to stationary power and gasoline applications, but includes markets where low sulfur diesel fuel is already available or has been mandated to coincide with future emission standards. In Japan, Toyota Motor Corporation has recently announced that it will begin introducing vehicles using its Diesel Particulate - NO_x Reduction (DPNR) system in 2003. This system uses a NO_x adsorber catalyst applied on the surface of a CDPF, providing greater than 80 percent reductions in both PM and NO_x. This system is being designed to operate with fuel in Japan that will have a 50 ppm sulfur cap but only with a regulated useful life of 50,000 miles (for heavy heavy-duty diesel engines in the US, the regulated useful life is 435,000 miles). Toyota notes, however, that the DPNR system requires fuel with low sulfur content in order to maintain high efficiency and good fuel economy for a long duration.⁴¹ In Europe, both Daimler Chrysler and Volkswagen, driven by a need to meet stringent Euro IV emission standards, have published results showing how they would apply the NO_x adsorber technology to their diesel-powered passenger cars. Volkswagen reports that it has already demonstrated NO_x emissions of 0.137 g/km (0.22 g/mi), a 71 percent reduction, on a diesel powered Passat passenger car equipped with a NO_x adsorber catalyst.⁴²

Likewise, in the United States, heavy-duty engine manufacturers have begun investigating the use of NO_x adsorber technologies as a more cost effective means to control NO_x emissions when compared to more traditional in-cylinder approaches. For example, Cummins Engine Company reported at DOE's 1999 Diesel Engine Emissions Reduction workshop, that they had demonstrated an 80 percent reduction in NO_x emissions over the Supplemental Steady State test using a NO_x adsorber catalyst.⁴³ In a separate presentation to members of the oil and engine industries, Cummins reported using a NO_x adsorber catalyst to demonstrate 98 percent NO_x control over the heavy-duty FTP, resulting in NO_x emissions of 0.055 g/bhp-hr from an engine out level of approximately 3 g/bhp-hr.⁴⁴

(b) DOE's DECSE Programs

The U.S. Department of Energy (DOE) has funded several test programs at national laboratories and in partnership with industry to investigate the NO_x adsorber technology. Most of these test programs are part of the Advanced Petroleum Based Fuel (APBF) program of DOE's Office of Transportation Technology (OTT). These programs are often referred to as the Diesel Emission Control Sulfur Effects (DECSE) program which is itself one of the APBF

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programs. Five reports documenting the DECSE program are available from the DOE OTT website (www.ott.doe.gov/decse) and were used extensively throughout our analysis.^{45 46 47 48 49}

At Oak Ridge National Laboratory DOE researchers have been working to demonstrate the application of a NO_x adsorber catalyst to a light-duty diesel passenger car. For this testing a Mercedes A170 diesel vehicle was evaluated on the light-duty chassis dynamometer driving cycle tests. The original equipment manufacturer (OEM) supplied catalysts were removed from the car and were replaced with a light-off catalyst, a NO_x adsorber catalyst and a synthesis gas reductant system (bottled gases). The synthesis gas reductant system was designed to simulate exhaust constituents that could be produced by in-cylinder late cycle injection. Overall, NO_x emissions were reduced by more than 90 percent when operating on three ppm sulfur diesel fuel. NO_x reductions of 89 percent were realized over the US06 test cycle while 96 percent reductions were realized over the SC03 test cycle. Subsequent testing of the vehicle revealed that poisoning of the catalyst with sulfur had substantially reduced the NO_x adsorber performance of the car in a little as 600 miles of driving on 150 ppm sulfur fuel.⁵⁰

The researchers concluded that NO_x adsorbers show promise for enabling significant reductions in diesel NO_x emissions based upon their demonstrated FTP and US06 emission results using a synthesis gas injection system to simulate late cycle, in-cylinder injection of diesel fuel. They further concluded that sulfur loading equivalent to 3,000 miles of operation on 30 ppm sulfur fuel caused a marked decrease in NO_x conversion and that commercial use of the NO_x adsorber will require effective desulfation, sulfur traps, or another solution to the sulfur poisoning problem.⁵¹

In the DECSE program, an advanced diesel engine equipped with common rail fuel injection and exhaust gas recirculation (EGR) was combined with a NO_x adsorber catalyst to control NO_x emissions. The system used an approach similar to the in-cylinder control approach described in section III.A.3.b.iii.a, above. Rich regeneration conditions are created for the NO_x adsorber catalyst regeneration through increased EGR rates and a secondary injection event designed to occur late enough in the engine cycle so as not to change engine torque output. Using this approach, the DECSE program has shown NO_x conversion efficiencies exceeding 90 percent over a catalyst inlet operating temperature window of 300°C to 450°C. This performance level was achieved while staying within the four percent fuel economy penalty target defined for regeneration calibration.⁵²

(c) NVFEL's NO_x Adsorber Evaluation Program

As part of an effort to evaluate the rapidly developing state of this technology, the Manufacturers of Emission Control Association (MECA) provided four different NO_x adsorber catalyst formulations to EPA for evaluation. Testing of these catalysts at the National Vehicle and Fuel Emission Laboratory (NVFEL) revealed that all four formulations were capable of

reducing NO_x emissions by more than 90 percent over the broad range of operation in the SET procedure (sometimes called the EURO III test). At operating conditions representative of “road-load” operation for a heavy duty on-highway truck, the catalysts showed NO_x reductions as high as 99 percent resulting in NO_x emissions well below 0.1 g/bhp-hr from an engine out level of nearly 5 g/bhp-hr. Testing on the FTP has shown similarly good results, with hot start FTP NO_x emissions reduced by more than 90 percent. These results demonstrate that significant NO_x reductions are possible over a broad range of operating conditions with current NO_x adsorber technology, as typified by the FTP and the SET procedures.

The test program at NVFEL can be divided into phases. The first phase began with an adsorber screening process using a single leg of the planned dual leg system. The goals of this screening process, a description of the test approach, and the results are described below. The next phase of the test program consisted of testing the dual leg system using a NO_x adsorber chosen during the first phase in each of two legs.

Testing Goals -- Single Leg NO_x Adsorber System

The goal of the NO_x adsorber screening process was to evaluate available NO_x adsorber formulations from different manufacturers with the objective of choosing an adsorber with 90 percent or better NO_x reduction for continued evaluation. To this end, four different adsorber formulations were provided from three different suppliers. Since this was a screening process and since a large number of each adsorber formulation would be required for a full dual leg system, it was decided to run half of a dual leg system (a single leg system) and mathematically correct the emissions and fuel economy impact to reflect a full dual leg system. The trade-off was that the single leg system would only be able to run steady state modes, as the emissions could not be corrected over a transient cycle. The configuration used for this test was similar to that shown in Figure III.A-4, but with a catalyst installed on only one side of the system.

Test Approach -- Single Leg NO_x Adsorber System

The single leg system consisted of an exhaust brake, a fuel injector, CDPF, and a NO_x adsorber in one test leg. The other leg, the “bypass leg,” consisted of an exhaust brake that opened when the test leg brake was closed; this vented the remainder of the exhaust out of the test cell. Under this set up, the test leg, i.e., the leg with the adsorber, was directed into the dilution tunnel where the emissions were measured and then compensated to account for emissions from the bypass leg. The restriction in the bypass leg was set to duplicate the backpressure of the test leg so that, while bypassing the test leg to conduct a NO_x regeneration, the backpressure of the bypass leg simulated the presence of a NO_x adsorber system. A clean-up diesel oxidation catalyst (DOC) downstream of the NO_x adsorber was not used for this testing.

The measured emissions had to be adjusted to account for the lack of any NO_x adsorber in the bypass leg. For this correction, it was assumed that the bypass leg's missing (virtual) adsorber would adsorb only while the actual leg was regenerating. It was also assumed the virtual adsorber would have regeneration fuel requirements in proportion to its adsorbing time. The emissions performance of the virtual adsorber was assumed to be the same as the performance of the actual adsorber. With these assumptions, the gaseous emissions could be adjusted as detailed in a memo to the docket describing this test program further.⁵³

Test Results -- Single Leg NO_x Adsorber System

Two sets of steady-state modes were run with each adsorber formulation. These modes consisted of the SET modes and the AVL 8 mode composite FTP prediction.¹ The modes are illustrated in Figure III.A-6 and are numbered sequentially one through 20 to include both the eight AVL modes and the 13 SET modes (the idle mode is repeated in both tests). The mode numbers shown in the figure are denoted as "EPA" modes in the subsequent tables to differentiate between the AVL and SET modes which have duplicate mode numbers. The NTE zones are also shown in Figure III.A-6 to show that these two sets of modes give comprehensive coverage of the NTE zone. The modes were run with varying levels of automation, with the general strategy being to inject sufficient fuel during regeneration to obtain a lambda at or slightly fuel rich of stoichiometric ($\lambda \leq 1$). The NO_x regenerations were then timed to achieve the desired NO_x reduction performance. The adsorber formulations were identified as A, B, D, and E. Prior to testing, each set of adsorbers were aged at 2500 rpm, 150 lb-ft for 40 minutes, then 2500 rpm full load for 20 minutes, repeated for a total of 10 hours.

¹ The AVL 8 mode test procedure is a steady-state test procedure developed by Anstalt für Verbrennungskraftmaschinen, Prof. Dr. Hans List (or Institute for Internal Combustion Engines) to approximate the transient FTP.

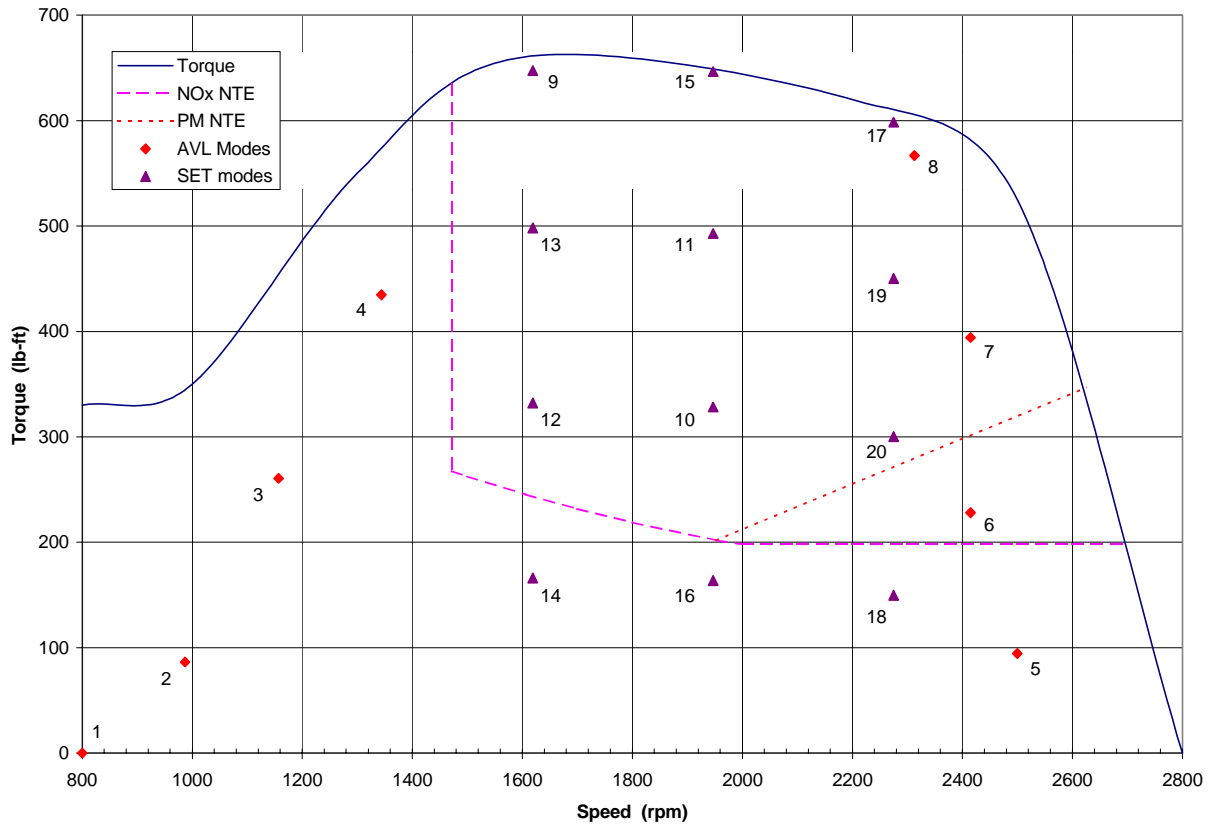


Figure III.A-6. Modal Definitions

(the mode numbers here correspond to the “EPA” modes given in the subsequent tables)

The SET and AVL Composite emission results, along with the NOx reduction performance vs. adsorber inlet temperature, are shown in Figures III.A-7 through III.A-10 for each of the tested NOx adsorber formulations. The SET composites for all four adsorber formulations had NOx reductions in excess of 90 percent with under a three percent FE impact. The HC emissions varied most widely, most likely due to differences in regeneration strategies, and to some extent, adsorber formulation. The HC emissions with the exception of adsorber “A” were very good, less than 0.1 g/hp-hr over the SET and less than 0.2 g/hp-hr over the AVL composite. It should be noted that no DOC was used to clean up the HC emissions.

Another point to note is that the EPA mode 1 data for each composite is the same. This is because EPA mode 1, low idle, is too cold for effective steady-state regeneration, but efficient NOx adsorption can occur for extended periods of time. For either of these composite tests, a regeneration would not be needed under such conditions and, therefore, the idle mode was

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considered to have no FE impact (See discussion in section III.A.3.b.iv of this chapter). EPA mode 1 has very little impact on either composite in any case because of the low power and emission rate. EPA mode 2 also had very low steady-state temperatures, and the difficulty regenerating at this mode can be seen in the HC and FE impacts. But, like EPA mode 1, EPA mode 2 would adsorb for extended periods of time without need for regeneration.

The AVL composite showed greater differences between the adsorber formulations than the SET. Three of the adsorbers achieved greater than 90 percent NO_x reduction over the AVL composites with the other adsorber at 84 percent NO_x reduction. The greater spread in NO_x reduction performance was, in part, due to this composite's emphasis on EPA mode 8, which was at the upper end of the NO_x reduction efficiency temperature window. Adsorber E had an EPA mode 8 NO_x reduction of 66 percent, and the NO_x reduction efficiency vs. inlet temperature graph clearly shows that this formulation's performance falls off quickly above 450°C. In contrast, the other formulations do not show such an early, steep loss in performance. The FE impacts vary more widely also, partly due to the test engineers' regeneration strategies, particularly with the low temperature modes, and to the general inability to regenerate at very low temperature modes at steady-state. It should be noted that none of the regeneration strategies here can be considered fully optimized, as they reflect the product of trial and error experimentation by the test engineers. With further testing and understanding of the technology a more systematic means for optimization should be possible. In spite of the trial and error approach the results shown here are quite promising.

The AVL composite was developed as a steady state engine-out emission prediction of the HDDE transient cycle. With exhaust emission control devices, it loses some of its accuracy because of the inability of the emission control devices to be regenerated at the low temperature modes (EPA modes 1, 2, 5). In real world conditions, the HDDE does not come to steady-state temperatures at any of these modes, and the adsorber temperatures will be higher at EPA modes 1, 2, and 5 than the stabilized steady-state values used for this modal testing. Consequently, the actual HDDE transient cycle performance is expected to be much better than the composites would suggest (See discussion of transient testing below).

Based on the composite data and the temperature performance charts, amongst other factors, adsorber formulation B was chosen for further dual leg performance work. Both composites for this formulation were well above 90 percent. The NO_x vs. temperature graph, Figure III.A-8, also shows that this formulation was a very good match for this engine.

Base						Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	461	0.11	98%	0.92	2.4%
10	3	10%	1947	328	4.7	357	0.07	98%	1.02	2.0%
11	4	10%	1947	493	5.0	411	0.06	99%	1.35	2.6%
12	5	5%	1619	332	5.0	384	0.13	97%	0.11	1.3%
13	6	5%	1619	498	5.0	427	0.24	95%	0.81	1.6%
14	7	5%	1619	166	5.5	287	0.25	95%	1.39	3.3%
15	8	9%	1947	630	4.0	498	0.89	78%	0.36	1.9%
16	9	10%	1947	164	5.0	293	0.14	97%	1.88	4.1%
17	10	8%	2275	599	4.0	515	0.48	88%	1.12	3.8%
18	11	5%	2275	150	4.8	282	0.42	91%	0.68	3.5%
19	12	5%	2275	450	5.0	404	0.08	98%	0.62	3.0%
20	13	5%	2275	300	4.8	357	0.14	97%	0.70	2.8%
Composite Results					4.6		0.31	93%	0.91 *	2.6% *

Base						Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	172	0.83	91%	0.75	7.7%
3	3	3%	1157	261	8.40	346	0.36	96%	1.10	3.1%
4	4	4%	1344	435	5.90	430	0.20	97%	2.16	3.0%
5	5	10%	2500	94	5.50	286	0.37	93%	4.93	3.6%
6	6	12%	2415	228	4.60	325	0.08	98%	2.30	3.6%
7	7	12%	2415	394	4.90	386	0.10	98%	2.38	3.1%
8	8	9%	2313	567	4.10	505	1.06	74%	0.03	1.9%
Composite Results					4.9		0.44	91%	1.69 *	2.9% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

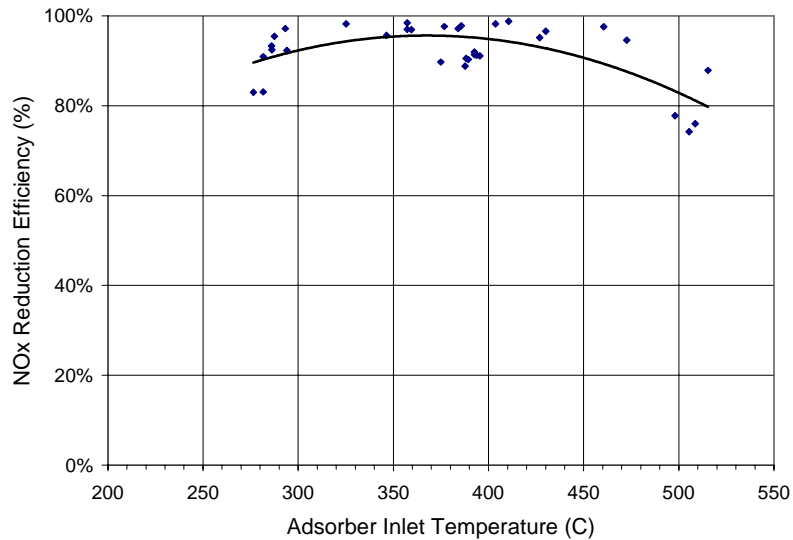


Figure III.A-7. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber A

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Base						Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	498	0.18	96%	0.01	1.2%
10	3	10%	1947	328	4.7	366	0.07	98%	0.04	0.5%
11	4	10%	1947	493	5.0	446	0.14	97%	0.01	1.5%
12	5	5%	1619	332	5.0	375	0.06	99%	0.08	0.7%
13	6	5%	1619	498	5.0	420	0.07	98%	0.10	2.3%
14	7	5%	1619	166	5.5	296	0.18	97%	0.10	0.3%
15	8	9%	1947	630	4.0	524	0.46	89%	0.01	3.2%
16	9	10%	1947	164	5.0	293	0.36	93%	0.05	0.4%
17	10	8%	2275	599	4.0	537	0.56	86%	0.04	4.3%
18	11	5%	2275	150	4.8	280	0.29	94%	0.03	0.4%
19	12	5%	2275	450	5.0	426	0.24	95%	0.04	4.3%
20	13	5%	2275	300	4.8	357	0.11	98%	0.02	0.9%
Composite Results						4.6	0.27	94%	0.03 *	2.2% *

Base						Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	162	0.56	94%	2.11	1.8%
3	3	3%	1157	261	8.40	355	0.30	96%	0.16	0.3%
4	4	4%	1344	435	5.90	446	0.09	98%	0.23	0.9%
5	5	10%	2500	94	5.50	263	0.66	88%	0.25	1.6%
6	6	12%	2415	228	4.60	346	0.11	98%	0.03	0.4%
7	7	12%	2415	394	4.90	403	0.05	99%	0.02	1.4%
8	8	9%	2313	567	4.10	544	0.73	82%	0.35	4.0%
Composite Results						4.9	0.33	93%	0.19 *	2% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

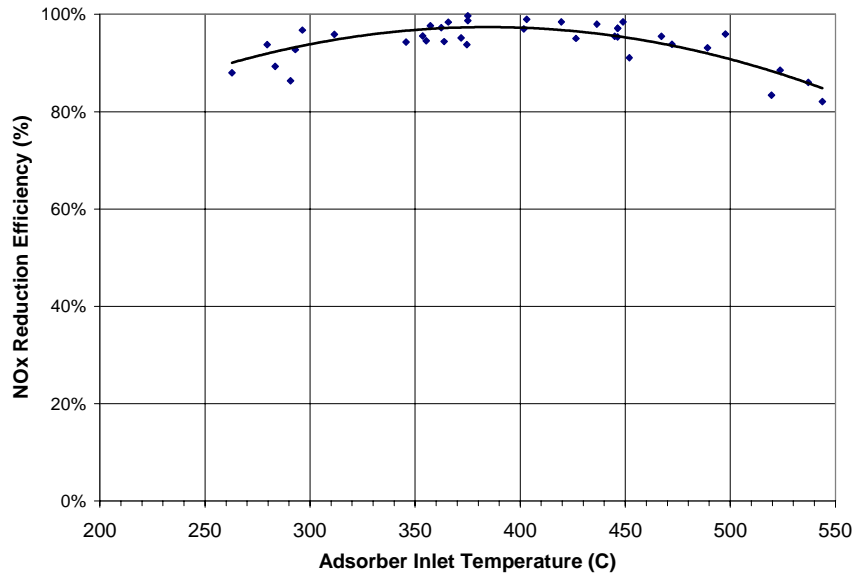


Figure III.A-8. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber B

Base						Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	15%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.60	451	0.18	96%	0.07	1.3%
10	3	10%	1947	328	4.70	356	0.14	97%	0.15	1.7%
11	4	10%	1947	493	5.00	400	0.09	98%	0.05	1.6%
12	5	5%	1619	332	5.00	377	0.07	99%	0.01	1.2%
13	6	5%	1619	498	5.00	431	0.11	98%	0.02	1.6%
14	7	5%	1619	166	5.50	305	0.23	96%	0.14	2.3%
15	8	9%	1947	630	4.00	501	0.16	96%	0.04	2.1%
16	9	10%	1947	164	5.00	303	0.15	97%	0.14	3.1%
17	10	8%	2275	599	4.00	489	0.93	93%	0.09	1.7%
18	11	5%	2275	150	4.80	278	0.57	88%	0.18	3.5%
19	12	5%	2275	450	5.00	391	0.12	98%	0.10	1.8%
20	13	5%	2275	300	4.80	330	0.21	96%	0.09	2.9%
Composite Results					4.6		0.28	94%	0.08 *	1.9% *

Base						Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	162	0.56	94%	2.11	1.8%
3	3	3%	1157	261	8.40	359	0.08	99%	0.30	3.1%
4	4	4%	1344	435	5.90	427	0.14	98%	0.19	1.7%
5	5	10%	2500	94	5.50	273	1.25	77%	0.26	6.4%
6	6	12%	2415	228	4.60	301	0.52	89%	0.13	1.9%
7	7	12%	2415	394	4.90	363	0.66	87%	0.04	1.4%
8	8	9%	2313	567	4.10	493	0.31	92%	0.08	1.6%
Composite Results					4.9		0.51	90%	0.14 *	1.9% *

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

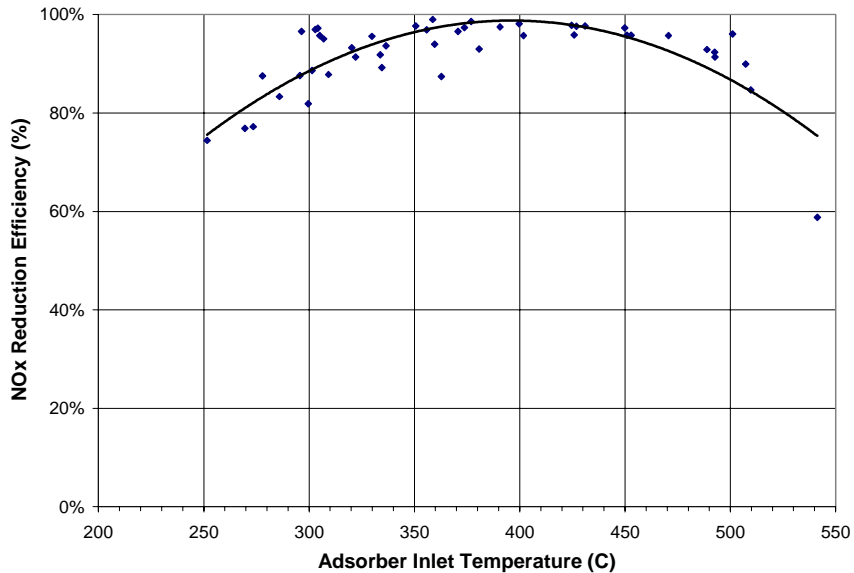


Figure III.A-9. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber D

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Base						Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	15%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.60	455	0.47	89%	0.02	2.1%
10	3	10%	1947	328	4.70	343	0.07	98%	0.05	0.9%
11	4	10%	1947	493	5.00	442	0.36	93%	0.07	9.0%
12	5	5%	1619	332	5.00	377	0.08	98%	0.01	1.5%
13	6	5%	1619	498	5.00	419	0.29	94%	0.03	1.6%
14	7	5%	1619	166	5.50	412	0.14	98%	0.05	1.7%
15	8	9%	1947	630	4.00	392	0.05	99%	0.02	2.1%
16	9	10%	1947	164	5.00	294	0.09	98%	0.26	4.4%
17	10	8%	2275	599	4.00	492	0.95	76%	0.03	2.0%
18	11	5%	2275	150	4.80	388	0.11	98%	0.03	2.4%
19	12	5%	2275	450	5.00	391	0.12	98%	0.10	1.8%**
20	13	5%	2275	300	4.80	327	0.22	95%	0.02	1.4%
Composite Results					4.6	** Md 19 data from Adsorber D 0.33 93% 0.05 * 2.9% *				

Base						Adsorber				
EPA Mode	AVL Mode	AVL Weighting	Speed (rpm)	Torque (lb-ft)	BSNOx (g/hp-hr)	Inlet T (C)	BSNOx (g/hp-hr)	NOx Red	HC *	FE Impact *
1	1	42%	Idle	0	13.00	144	0.16	100%	0.00	0.0%
2	2	8%	987	86	8.80	166	7.39	16%	1.02	71.9%
3	3	3%	1157	261	8.40	339	0.09	99%	0.05	2.3%
4	4	4%	1344	435	5.90	449	0.65	89%	0.01	2.1%
5	5	10%	2500	94	5.50	256	1.36	75%	0.91	15.8%
6	6	12%	2415	228	4.60	313	0.35	92%	0.21	5.6%
7	7	12%	2415	394	4.90	372	0.12	97%	0.10	2.6%
8	8	9%	2313	567	4.10	508	1.39	66%	0.04	3.3%
Composite Results					4.9	0.80 84% 0.16 * 5.4% *				

* HC results & FE Impacts do not reflect future potential as they are derived using a 5 g NOx engine which requires more frequent NOx regens than would result using a 2.5 g engine and the tested system was not a fully optimized engine & emission control system.

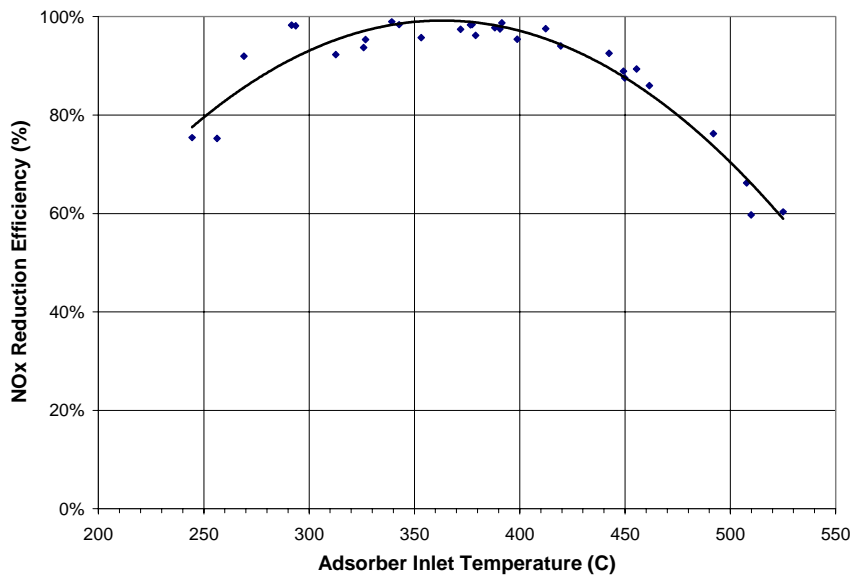


Figure III.A-10. SET & AVL Composites, and Temperature vs. NOx Chart for Adsorber E

Testing Goals -- Dual Leg NOx Adsorber System

After completing the screening process and selecting NOx adsorber “B,” the dual leg system was developed. The testing goal for the dual leg system was to demonstrate that NOx adsorbers are capable of 90 percent NOx reductions over the HD FTP and SET tests with a current production engine. Once the capability of the devices to achieve the NOx reductions is established, testing will be done to evaluate the impact of higher fuel sulfur levels (15 ppm) and aging effects on adsorber performance.

Testing Approach -- Dual Leg NOx Adsorber System

The steady state SET testing was conducted in a manner similar to that used in the screening process described above. The modes were run with varying levels of automation, with the general strategy being to inject sufficient fuel during regeneration to obtain a lambda at or slightly fuel rich of stoichiometric ($\lambda \leq 1$). The NOx regenerations were then timed to achieve the targeted 90 percent NOx reduction. Each mode was run twice by different calibrators to investigate the adsorber’s emission and fuel usage sensitivity to different combinations of regeneration frequency and fuel injection rates. The regeneration control and optimization strategies are described in more detail in a memo to the docket for this rule.⁵⁴ The engine and the integrated dual-bed NOx adsorber/CDPF system are also described in more detail in section III.A.3.b.iii.

The transient HDDE FTP regeneration control was accomplished using a time-based regeneration schedule. This control regenerated on a prescribed schedule of time and fuel quantities so that regenerations occurred at predetermined engine conditions during the transient cycle. This control represents a simplified control strategy that was used due to the lack of time to develop a true, non-time based control algorithm.

The transient HDDE FTP results presented here are for hot-start cycles only. The adsorber system was not optimized for cold start performance and would not provide a meaningful assessment of adsorber warmup performance. In order to better simulate the “cold-soak-hot” procedure called for in the HDDE FTP, a preconditioning mode was chosen to provide adsorber temperatures at the start of the “hot” cycle that would be similar to those found following the “cold-soak” portion of the test. The mode chosen was EPA mode 10 (1947 rpm, 328 lb-ft) which resulted in adsorber inlet temperatures (i.e., at the outlet of the CDPF) at the start of the hot cycle of about 280°C. Another purpose for the preconditioning was to ensure the adsorbers were in the same condition at the start of each test. Given that our regeneration control system did not automatically take into account the starting condition of the NOx adsorbers, this preconditioning was necessary to provide repeatable transient test results. We expect more realistic control systems would not need such preconditioning. For this preconditioning, the

adsorbers were regenerated frequently in order to ensure a consistent, relatively clean adsorber state at the start of the transient cycle. The preconditioning consisted of 30 seconds of regeneration followed by 30 seconds of adsorption as shown below in Figure III.A-11.

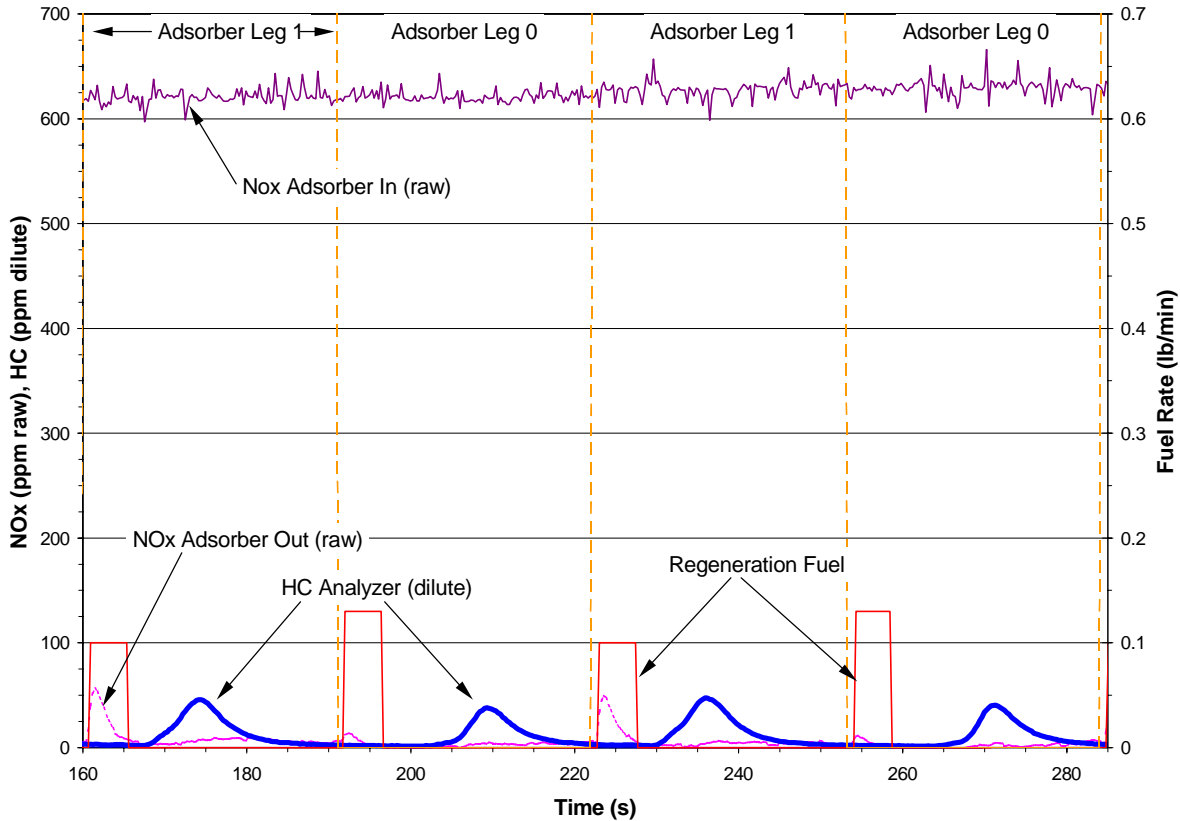


Figure III.A-11. NOx Adsorber FTP Preconditioning Cycle used in NVFEL Testing

Test Results -- Dual Leg NOx Adsorber System

Supplemental Emission Test (SET) Results

The SET is made up of the 13 Euro III modes. Several modes were run twice by different engineers, and the best calibration was chosen for the SET composite. Table III.A-2 shows the SET composite test results. These data show that 90 percent NOx reductions were possible over the SET composite, with a modal NOx reduction range from 77 percent to 98 percent. The adsorber NOx and HC reduction performance varied primarily as a function of exhaust temperature. Modes with high temperatures (>500°C) tended to have lower NOx reduction performance with this adsorber formulation. High temperature EPA modes 9, 15 and 17 had

lower performance due to the conflict between the high NO_x mass flow rate from the engine, the reduced storage capacity of the NO_x adsorber due to ongoing sulfur poisoning and the reduction in storage capacity near 500°C observed for this adsorber. The combination of these three factors resulted in higher NO_x slippage during adsorption.

Table III.A-2. SET Composite Test Results with the Dual Leg NO_x Adsorber System

Base						Adsorber				
EPA Mode	SET Mode	SET Weighting	Speed (rpm)	Torque (lb-ft)	BSNO _x (g/hp-hr)	Inlet T (C)	BSNO _x (g/hp-hr)	NO _x Red	HC (g/hp-hr)	FE Impact
1	1	15%	Idle	0	13.0	144	0.16	100%	0.00	0.0%
9	2	8%	1619	630	4.6	493	0.71	84%	0.16	1.8%
10	3	10%	1947	328	4.7	373	0.09	98%	0.28	2.3%
11	4	10%	1947	493	5.0	444	0.17	96%	0.24	2.8%
12	5	5%	1619	332	5.0	404	0.07	98%	0.14	2.6%
13	6	5%	1619	498	5.0	456	0.51	90%	0.11	1.9%
14	7	5%	1619	166	5.5	304	0.28	95%	0.11	2.5%
15	8	9%	1947	630	4.0	521	0.56	86%	0.31	2.2%
16	9	10%	1947	164	5.0	343	0.34	93%	0.09	1.9%
17	10	8%	2275	599	4.0	510	0.91	77%	0.54	1.8%
18	11	5%	2275	150	4.8	283	0.22	95%	0.56	3.0%
19	12	5%	2275	450	5.0	409	0.41	92%	0.13	1.8%
20	13	5%	2275	300	4.8	361	0.12	98%	0.10	2.0%
Composite Results					4.6		0.45	90%	0.27	2.1%

Conversely, low exhaust temperatures did not seem to impact the NO_x storage capability of the adsorber. The ability to store at low temperatures is reflected in the low idle, EPA mode 1 performance. Nearly 100 percent NO_x reduction could be realized for several minutes until the adsorber's storage sites filled up with NO_x, particularly when coming down to low idle from higher temperature modes. NO_x regeneration at low idle after the adsorber had cooled to a low steady-state temperature was not possible with this adsorber in our testing.

The FE impact was defined as the percent increase in fuel consumption caused by the adsorber regeneration fuel, or the mass of fuel used for regeneration, divided by the mass of fuel consumed by the engine during one regeneration and adsorption cycle. The FE impact varied from 1.8 to 3.0 percent depending on the mode. The low temperature modes (EPA modes 14, and 18) tended to have higher FE impacts. This was caused by the combination of low engine fuel consumption and low HC utilization efficiency seen with this catalyst at these temperatures. Given the short time spent calibrating the regeneration events, and the relatively early stage of catalyst development, we anticipate significant improvements in regeneration strategies will be possible.

Finally, at the time these SET emission tests were conducted, the NO_x adsorber system had accumulated 172 hours of operation. During that time, 530 gallons of five ppm equivalent

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(some three ppm and some six ppm) sulfur fuel was consumed by the engine and the NO_x adsorber regenerations. For a light heavy-duty diesel truck averaging 20 miles per gallon of fuel, the 530 gallons of fuel consumed here would be equivalent to more than 10,000 miles of driving. No desulfations were performed during any of the testing, though it is expected that a NO_x adsorber system in-use would have been desulfated at least twice, and more likely three times, during this amount of driving. Consequently, the adsorbers' performance would likely have been even better had they been desulfated as anticipated.

HDDE Transient FTP Test Results

The transient cycle data were taken with a DOC downstream of the NO_x adsorbers and insulation on the exhaust from the engine to the CDPF. Table III.A-3 shows a timed regeneration schedule that was developed to switch between adsorbers, and to control when and how much fuel was injected for NO_x regeneration. The first column in the table, "Time," represents the time from the start of the FTP and is used as a trigger to switch which leg is adsorbing. That is, at 30 seconds, and 60 seconds, etc., the adsorbing leg is bypassed and the previously bypassed leg starts adsorbing. The second column, "Fuel Rate," is the rate that fuel is injected into the bypassed (regenerating) adsorber. The final column is the time for which the fuel is injected at the rate specified in the previous column.

Figure III.A-3. Timed Regeneration Schedule for Switching between NO_x Adsorber Legs

Time (s)	Fuel Rate (lb/min)	Injection Time (s)		Time (s)	Fuel Rate (lb/min)	Injection Time (s)
20	0	0		705	0.25	1.0
40	0	0		725	0.25	1.0
60	0	0		750	0.25	1.0
80	0	0		775	0.25	1.5
120	0.25	2.0		800	0.25	1.0
180	0.25	2.0		825	0.25	1.0
240	0.25	1.4		850	0.25	1.3
260	0.25	2.0		875	0.25	1.2
320	0.25	2.0		900	0.25	1.3
410	0.25	1.0		945	0	0
430	0.25	1.5		975	0	0
470	0.25	1.5		995	0.25	2.0
500	0.25	1.2		1070	0.25	2.0
530	0.25	1.5		1145	0	0
580	0.25	1.8		1165	0	0
630	0.25	1.0		1185	0	0
655	0.25	1.0		1200	0	0
680	0.25	1.0				

This regeneration strategy resulted in an average, over three HDDE FTPs, of 0.25 g/hp-hr NO_x, 0.002 g/hp-hr PM and virtually no CO (See Table III.A-4). These represent greater than 90 percent reductions from the engine out emission levels. HC emissions decreased slightly compared to the baseline results. The relatively small HC emission increase was the result of HC slippage during NO_x regeneration. Two factors contributed to the HC slippage. One factor was the relatively low HC oxidation efficiency of the DOC used downstream of the adsorbers. Back-to-back testing with a raw gas analyzer at several steady state modes revealed that the lightly catalyzed DOC (~10 g/ft³ Pt) had an oxidation efficiency of less than 60 percent, where more effective DOCs are capable of 90 percent HC reductions. The second factor was that more fuel was injected than was absolutely necessary to release and reduce the stored NO_x. The excess HC then contributed to HC emissions and FE Impact. Determining the best strategy for injecting the fuel so that it is most efficiently utilized will be important future work.

Table III.A-4. HDDE FTP Emissions from NVFEL Test Program

Emission	Run # 1	Run # 2	Run # 3	Average	Engine Out
NO _x (g/hp-hr)	0.26	0.25	0.40	0.25	3.66
HC (g/hp-hr)	0.28	0.30	0.19	0.28	0.29
CO (g/hp-hr)	0.00	0.00	0.04	0.00	1.46
PM (g/hp-hr)	0.003	0.002	0.002	0.002	0.089
FE Impact (%)	2.4	2.3	2.3	2.3	-

At the time these FTP emission tests were conducted, the NO_x adsorber system had accumulated 190 hours of operation. During that time, 653 gallons of five ppm equivalent (some three ppm and some six ppm) sulfur fuel was consumed by the engine and the NO_x adsorber regenerations. For a light heavy-duty diesel truck averaging 20 miles per gallon of fuel, the 653 gallons of fuel consumed here would be equivalent to more than 13,000 miles of driving. No desulfations were performed during any of the testing, though it is expected that a NO_x adsorber system in-use would have been desulfated at least twice, and more likely three or four times, during this amount of driving. Consequently, the adsorbers' performance would likely have been even better had they been desulfated as anticipated.

vi. *Can a NO_x Adsorber Equipped Diesel Engine Meet the NO_x Standards?*

(a) The FTP Standard

As discussed in section III.A.3.b.v.c, above, we have demonstrated in our laboratory that a NO_x adsorber can produce greater than 90 percent reduction in NO_x emissions over the hot-start HDDE transient FTP. The results of this test program lead us to believe NO_x adsorbers will be capable of meeting the Phase 2 FTP NO_x emission standard of 0.20 g/bhp-hr. The test program discussed under section III.A.3.b.v.c utilized a non-EGR equipped engine certified to the 1999 HD standards (i.e., the 4.0 g/bhp-hr NO_x standard). As discussed in more detail in the test report in the docket which documents that test program, the regeneration strategy we used to produce the greater than 90 percent reduction had significant room for improvement.⁵⁵ For example, the raw data collected during the FTP runs indicated numerous regeneration events which were either unnecessary (because the adsorber bed was not slipping NO_x) or regeneration events which released NO_x but did not reduce the released NO_x because the adsorber did not achieve a locally rich condition. We conclude from this initial test program that NO_x reductions greater than 90 percent are achievable.

As mentioned, the data presented in Table III.A-4 is from an HDDE certified to the 4.0 g/bhp-hr NO_x FTP standard. If the engine-out levels are reduced to achieve the 2004 FTP standards through the use of cooled EGR, our understanding of how the NO_x adsorber technology works leads us to believe NO_x adsorbers would also be capable of achieving 90 percent or greater emission reduction on a 2004 technology engine. Therefore, a NO_x adsorber used on an HDDE certified to the Phase 1 FTP standard of 2.5 g/bhp-hr NMHC+NO_x would enable a HDDE to achieve the Phase 2 FTP NO_x standard. In addition, as discussed in section III.A.3.b.v.a of this chapter, one HDDE manufacturer has also demonstrated greater than a 98 percent NO_x reduction over the HD FTP using a NO_x adsorber.⁵⁶

The results discussed above have all been demonstrated over the hot-start portion of the HDDE FTP, but the HD FTP also includes a cold-start test. A complete HDDE FTP involves three test sequences. First, the 20 minute duty-cycle test is run with the engine at the same ambient temperature as the test cell (between 68°F and 86°F). This can be achieved with a long soak period, or a forced engine cool-down. Second, following the cold-start run the engine undergoes a hot-soak which lasts 10 minutes. Finally, the 20 minute duty-cycle test is run a second time. The HDDE FTP emission level for the engine is determined by weighting the cold-start emissions by 1/7 (~14 percent), and weighting the hot-start emission results by 6/7 (~86 percent). Historically, for a HDDE not equipped with an exhaust emission control device, the cold-start and hot-start emissions from a HDDE have been nearly identical. However, with the application of exhaust emission control devices, such as a NO_x adsorber, the cold-start test will become a design challenge for diesel manufacturers, just as it has been a design challenge for light-duty gasoline vehicle manufacturers for more than 20 years. As discussed above, NO_x

adsorbers do have optimal temperature operating windows, and thus will represent a design challenge.

Manufacturers have a number of tools available to them to overcome this challenge:

- The volume, shape, and substrate material have a significant effect on the warm-up time of a NO_x adsorber (just as they do for a light-duty three-way catalysts). Manufacturers will optimize the make-up of the adsorber for best light-off characteristics, such as the thin-walled ceramic monolith catalysts typical of modern low emission light-duty gasoline applications.
- The packaging of the exhaust emission control devices, including the use of insulating material and air-gap exhaust systems, will also decrease light-off time, and we expect manufacturers to explore those opportunities.
- The location of the adsorber, with respect to its proximity to the exhaust manifold, will have a significant impact on the light-off characteristics.
- As discussed in more detail in section III.A.3.b.iv.a, NO_x adsorbers have the ability to store NO_x at temperatures much less than the three-way catalyst function temperature operating window, on the order of 100°C. This is unlike the performance of light-duty gasoline catalysts, and it would allow the NO_x adsorber to store NO_x for some period of time prior to the light-off time of the three-way function of its catalyst, resulting in an overall lower effective temperature for the device.

These first four tools available to manufacturers all deal with system design opportunities to improve the cold-start performance of the NO_x adsorber system. In addition, manufacturers have a number of active tools which can be used to enhance the cold-start performance of the system. These include the use of engine start-up routines which have a primary purpose of adding heat to the exhaust to enhance NO_x adsorber light-off. For example:

- retarded injection timing;
- intake air throttling;
- post-injection addition of fuel; or
- or increasing back-pressure with an exhaust brake or a VGT system.

Chapter III: Emissions Standards Feasibility

We anticipate manufacturers will explore all of these tools in order to choose the best combination necessary to minimize light-off time and improve the cold-start FTP performance. Considering that the cold-start test is weighted approximately 14 percent, a manufacturer could achieve the composite FTP standard with considerably less than 90 percent reduction over the cold-start test, provided the hot-start test achieves greater than 90 percent reduction. Considering the tools available to manufacturers, and the several years of lead time, we conclude the cold-start FTP challenges will not be a barrier to the achievement of the FTP NO_x standard established in this rule.

Based on the data and discussion provided in this section, we conclude that the Phase 2 FTP NO_x standard is technologically feasible.

(b) The Supplemental Emission Test (SET) NO_x Standard

The SET NO_x requirements established in the Phase 1 rule for 2007 sets an NMHC+NO_x standard equal to 1.0 x the Phase 1 FTP standard of 2.5 g/bhp-hr NMHC+NO_x. Based on current certification data for HDDE's which indicate HC values on the order of 0.2 to 0.3 g/bhp-hr, we anticipate that Phase 1 technology engines will achieve the SET standard with NO_x emissions on the order of 2.2 to 2.3 g/bhp-hr. The SET standard promulgated with this Phase 2 rule sets a NO_x standard of 1.0 x the Phase 2 FTP NO_x standard of 0.20 g/bhp-hr. This requires a NO_x reduction on the order of 90 percent or more from Phase 1 technology engines, which we have demonstrated is achievable with NO_x adsorber technology, as discussed below.

Section III.A.3.b.iv.c discusses the NO_x adsorber NO_x reduction efficiencies as a function of exhaust gas temperature. The majority of these data show emission reductions of greater than 90 percent are achievable across the range of exhaust gas temperatures typical of a HDDE during the SET test procedure.

Section III.A.3.b.v.c contains SET emissions data from four different NO_x adsorbers using a single-bed exhaust configuration tested at NVFEL. This test data shows NO_x reductions for the SET between 93 and 94 percent. Section III.A.3.b.v.c also contains SET test data collected using a dual-bed exhaust configuration which achieved a 90 percent NO_x reduction.

Based on the information presented in this Chapter, and summarized above, we conclude that the SET NO_x standard will be technologically feasible by model year 2007.

(c) The Not-to-Exceed NO_x Standard

Under the Phase 1 HDDE rule, NTE emission requirements for NMHC+NO_x specify the NTE standard as 1.25 x FTP standard. The Phase 1 FTP standard for NMHC+NO_x is 2.5 g/bhp-hr, therefore the Phase 1 NMHC+NO_x NTE standard is 3.1 g/bhp-hr. As discussed in the Phase

1 final rule, we would expect the break-down between NMHC and NO_x emissions for the Phase 1 NTE standard to mostly NO_x emissions, on the order of 3.0 g/bhp-hr NO_x, with the remainder being NMHC. In this rule, we have promulgated the Phase 2 engine NO_x NTE standard as 1.5 x FTP standard, i.e., 1.5 x 0.20 g/bhp-hr, which is 0.30 g/bhp-hr NO_x. Therefore, a 90 percent reduction in NO_x emissions is necessary from Phase 1 engines in order to achieve the Phase 2 NTE NO_x standard in this final rule. As discussed below, this 90 percent reduction is technologically feasible by model year 2007 across the range of engine operating conditions and ambient conditions subject to the NTE standards specified in this rule. Also as discussed below, some modifications to the NTE provisions to address technical issues which arise from the application of advanced NO_x catalyst systems have been included in this final rule.

Section III.A.3.b.v.c (“NVFEL’s NO_x Adsorber Evaluation Program”), contains a description of the NO_x adsorber evaluation test program run by our EPA laboratory. Included in that section is test data on four different NO_x adsorbers for which extensive steady-state mapping was performed in order to calculate the SET and AVL composites (See Figures III.A-7 through III.A-10). Several of the test modes presented in these figure are not within the NTE NO_x control zone, and would not be subject to the NTE standard. The following modes listed in these four figures are within the NTE NO_x control zone, EPA modes 6 - 13, 15, 17, 19, 20. For all of the adsorbers, efficiencies of 90 percent or greater were achieved across the majority of the NTE zone. The region of the NTE zone for which efficiencies less than 90 percent were achieved were concentrated on or near the torque curve (EPA modes 8, 9, 15 and 17) with the exception of Adsorber D, for which EPA modes 6 and 7 achieved 87 percent and 89 percent NO_x reduction respectively. However, Adsorber D was able to achieve NO_x reductions greater than 90 percent along the torque curve. The test modes along the torque curve represent the highest exhaust gas temperature conditions for this test engine, on the order of 500°C. As discussed in Section III.A.3.b.iv.c, 500°C is near the current upper temperature limit of the peak NO_x reduction efficiency range for NO_x adsorbers, therefore it is not unexpected that the NO_x reductions along the torque curve for the test engine are not as high as in other regions of the NTE zone. We would expect manufacturers to choose a NO_x adsorber formulation which matches the exhaust gas temperature operating range of the engine. In addition, the steady-state mode data in section III.A.3.b.v.c were collected under stabilized conditions. In reality, actual in-use operation of a heavy-duty diesel vehicle would likely not see periods of sustained operation along the torque curve, and therefore the likelihood the NO_x adsorber bed itself would achieve temperatures in excess of 500°C would be diminished. Regardless, as discussed in Section III.A.3.b.iv.a & c, we expect incremental improvements in the high temperature NO_x reduction capabilities of NO_x adsorbers between now and model year 2007 will be achieved through improvements in NO_x adsorber formulations.^{57, 58} As discussed above, only small improvements in the current characteristics are necessary in order to achieve 90 percent NO_x reductions or greater across the NTE control zone.

As discussed in section III.A.3.b.vi.a, the use of advanced NO_x reduction catalyst systems on HDDEs will present cold-start challenges for HDDEs similar to what light-duty gasoline manufacturers have faced in the past, due to the light-off characteristics of the NO_x adsorber. We have previously discussed the tools available to HDDE manufacturers to overcome these challenges in order to achieve the Phase 2 FTP NO_x standard. The majority of engine operation which occurs within the NTE control zone will occur at exhaust gas temperatures well above the light-off requirement of the NO_x adsorbers. Figures III.A-7 through III.A-10 in section III.A.3.b.v.c (“NVFEL’s NO_x Adsorber Evaluation Program”) show that all test modes which are within the NTE control zone have exhaust gas temperatures greater than 300°C which, as discussed in section III.A.3.b.iv, is well within the peak NO_x reduction efficiency range of current generation NO_x adsorbers. However, though the NTE does not include engine start-up conditions, it is conceivable that a HDDE vehicle which has not been warmed up could be started and very quickly be operated under conditions which are subject to the NTE standard; for example, within a minute or less of vehicle operation after the vehicle has left an idle state. The NTE regulations specify a minimum emissions sampling period of 30 seconds. Conceivably the vehicle emissions could be measured against the NTE provisions during that first minute of operation, and in all likelihood it would not meet the NTE NO_x standard set in this final rule. Given that the FTP standards will require control of cold-start emissions, manufacturers will be required to pay close attention to cold start to comply with the FTP. As discussed above, operation with the NTE will be at exhaust gas temperatures within the optimum NO_x reduction operating window of the NO_x adsorbers. In addition, the NO_x adsorber is capable of adsorbing NO_x at temperatures on the order of 100°C. Figures III.A-7 through II.A.-10 all show NO_x emission reductions on the order of 70 - 80 percent are achieved at temperatures as low as 250°C. Therefore, we have established a low temperature exhaust gas threshold of 250°C, below which specified NTE requirements do not apply.

The minimum emissions sample time established under the Phase 1 rule for NTE testing is 30 seconds. This testing requirement was premised on the use of Phase 1 HDDE emission control technology such as EGR and fuel injection timing. These emission control devices tend to produce brake-specific mass emission rates of exhaust pollutants which do not have periodic, orders of magnitude changes in brake-specific emission rates within the NTE control zone when averaged over a 30 second sample time. However, this is not the case for the NO_x adsorber catalysts. As discussed throughout this Chapter, NO_x adsorbers require active regeneration events, which can produce near zero mass emission rates during the adsorption phase, followed by relatively large spikes in NO_x and HC emissions during the regeneration phase. This is illustrated in Figure III.A-11, above, which shows that engine out NO_x under steady-state conditions on the order of 640 ±15 ppm, which is fairly continuous. However, the NO_x emissions downstream of the NO_x adsorber are both much lower and are characterized by periodic, orders of magnitude changes in emissions. The NO_x concentration downstream of the adsorber shows periods of near zero ppm NO_x lasting approximately 10 seconds, followed by a NO_x peak with a maximum concentration of approximately 40 ppm, with the spike lasting

approximately four seconds. A similar phenomenon can be seen in Figure III.A-11 for hydrocarbon emissions. Because of this unique periodic nature of the NO_x adsorber system, we have modified the NTE sample time provisions in the regulations, to assure that the emission spikes described above are not measured in isolation during NTE testing. The regulations specify that for any emission control system which requires discreet regeneration events, if a regeneration event occurs within the emissions sample, the emissions averaging time must be at least as long as the time between regenerations events (i.e., a regeneration period), multiplied by the number of full regeneration events within the sample period. This provision to account for regeneration events ensures that the unique operation of the NO_x adsorber system will not cause an inappropriate exceedance of the NTE limits.

The NTE requirements apply not only during laboratory conditions applicable to the transient FTP and the SET tests, but also under the wider range of ambient conditions for altitude, temperature and humidity specified in the regulations. These expanded conditions will have minimal impact on the emission control systems expected to be used to meet the NTE NO_x standard contained in this final rule. Under the Phase 1 rule, NTE emissions under the expanded NTE testing conditions can be as high as 3.1 g/bhp-hr NMHC+NO_x (1.25 x 2004 FTP standard). Therefore, we assume here that engines in the 2007 time frame are capable of achieving 3.1 g/bhp-hr NMHC+NO_x over the NTE without the use of the NO_x control devices needed to achieve the standards contained in this rule. Thus, we analyze the impact of the NTE expanded testing conditions on the NO_x adsorber, not on the base engine which is capable of achieving the Phase 1 NTE requirements. In general, it can be said that the performance of the NO_x adsorbers are only effected by the exhaust gas stream to which the adsorbers are exposed. Therefore, the impact of ambient humidity, temperature, and altitude will only effect the performance of the adsorber to the extent these ambient conditions change the exhaust gas conditions (i.e., exhaust gas temperature and gas constituents). The ambient humidity conditions subject to the NTE requirement will have minimal, if any, impact on the performance of the NO_x adsorbers. The exhaust gas itself, independent of the ambient humidity, contains a very high concentration of water vapor, and the impact of the ambient humidity on top of the products of dry air and fuel combustion are minimal. The effect of altitude on NO_x adsorber performance should also be minimal, if any. The NTE test procedure regulations specify an upper bound on NTE testing for altitude at 5,500 feet above sea-level. The Phase 1 regulations require compliance with an NTE NMHC+NO_x limit of 1.25 x the Phase 1 FTP standard up to this altitude. As discussed above, a 90 percent reduction in NO_x emissions from the Phase 1 technology engines is, therefore, necessary to comply with the NTE standard established in this rule. The decrease in atmospheric pressure at 5,500 feet should have minimal impact on the NO_x adsorber performance. Increasing altitude can decrease the air-fuel ratio for HDDEs which can in turn increase exhaust gas temperatures; however, as discussed in the Phase 1 final rule, Phase 1 technology HDDEs can be designed to target air-fuel ratios at altitude which will maintain appropriate exhaust gas temperatures, as well as maintain engine-out PM levels near the 0.1 g/bhp-hr level, within the ambient conditions specified by the NTE test procedure. Finally, the NTE regulations specify

ambient temperatures which are broader than the FTP temperature range of 68-86°F. The NTE test procedure specifies no lower ambient temperature bounds. However, as discussed above, we have limited NTE requirements on NO_x (and HC) for engines equipped with NO_x (and/or HC) catalysts to include only engine operation with exhaust gas temperatures greater than 250°C. Therefore, low ambient temperatures will not present any difficulties for NTE NO_x compliance. The NTE also applies under ambient temperatures which are higher than the FTP laboratory conditions. The NTE applies up to a temperature of 100°F at sea-level, and up to 86°F at 5,500 feet above sea-level. At altitudes in between, the upper NTE ambient temperature requirement is a linear fit between these two conditions. At 5,500 feet, the NTE ambient temperature requirement is the same as the upper end of the FTP temperature range (86°F), and therefore will have no impact on the performance of the NO_x adsorbers, considering that majority of the test data described throughout this chapter was collected under laboratory conditions. The NTE upper temperature limits at sea-level is 100°F, which is 14°F (7.7°C) greater than the FTP range. This increase is relatively minor, and while it will increase the exhaust gas temperature, in practice the increase should be passed through the engine to the exhaust gas, and the exhaust gas would be on the order of 8°C higher. Within the exhaust gas temperature range for a HDDE during NTE operation, an 8°C increase is very small. As discussed above, we expect manufacturer to choose an adsorber formulation which is matched to a particular engine design, and we would expect the small increase in exhaust gas temperature which can occur from the expanded ambient temperature requirements for the NTE will be taken into account by the manufacturer when designing the complete emission control system.

To summarize, based on the information presented in this Chapter, and the analysis and discussion presented in this section, we conclude the NTE NO_x requirement (1.5 x FTP standard) contained in this final rule will be feasible by model year 2007.

vii. Are Diesel NO_x Adsorbers Durable?

The considerable success in demonstrating NO_x adsorbers, as outlined above, makes us confident that the technology is capable of providing the level of conversion efficiency needed to meet the NO_x standard. However, there are several engineering challenges that will need to be addressed in going from this level of demonstration to implementation of durable and effective emission control systems on production vehicles. In addition to the generic need to optimize engine operation to match the NO_x adsorber performance, industry will further need to address issues of system and catalyst durability. The nature of these issues are understood well today. The hurdles that must be overcome have direct analogues in technology issues that have been addressed previously in other automotive applications and are expected to be overcome with many of the same solutions. In this section we will describe the major technical hurdles to address in order to ensure that the significant emission reductions enabled through the application of NO_x adsorbers is realized throughout the life of heavy-duty diesel vehicles. The

section is organized into separate durability discussions for the system components (hardware) and various near and long term durability issues for the NO_x adsorber catalyst itself.

(a) NO_x Adsorber Regeneration Hardware Durability

The system we have described in Figure III.A-4 represents but one possible approach for generating the necessary exhaust conditions to allow for NO_x adsorber regeneration and desulfation. The system consists of three catalyst substrates (for a CDPF/Low Temperature NO_x Adsorber, a High Temperature NO_x Adsorber and an Oxidation Catalyst), a support can that partitions the exhaust flow through the first two catalyst elements, three fuel injectors, and a means to divert exhaust flow through one or more of the catalyst partitions. Although not shown in the figure, a NO_x /O₂ sensor is also likely to be needed for control feedback and on-board diagnostics(OBD). All of these elements have already been applied in one form or another to either diesel or gasoline engines in high volume long life applications.

The environment in an automotive exhaust system is extremely harsh with high temperatures, high humidity and high levels of mechanical vibration. For all of these reasons care is taken to design components to function over the life of a vehicle. Despite these challenging conditions, technologies have been developed over the last 30 or more years that are well suited to exhaust conditions. One of the most ubiquitous components on a modern passenger car is the three-way catalyst. Its design has evolved over the years so that today it is highly efficient, reliable and durable.

The NO_x adsorber system we described earlier borrows several components from the gasoline three-way catalyst systems and benefits from the years of development on three way catalysts. The catalyst substrates (the ceramic support elements on which a catalyst coating is applied) have developed through the years to address concerns with cracking due to thermal cycling and abrasive damage from vehicle vibration. The substrates applied for diesel NO_x adsorbers will be virtually identical to the ones used for today's passenger cars in every way but size. They are expected to be equally durable when applied to diesel applications as has already been shown in the successful application of diesel oxidation catalysts (DOCs) on some diesel engines over the last 10 years.

The NO_x/O₂ sensor needed for regeneration control and OBD is another component originally designed and developed for gasoline powered vehicles (in this case lean-burn gasoline vehicles) that are already well developed and can be applied with confidence in long life for NO_x adsorber based diesel emission control. The NO_x/O₂ sensor is an evolutionary technology based largely on the current Oxygen (O₂) sensor technology developed for gasoline three-way catalyst based systems. Oxygen sensors have proven to be extremely reliable and long lived in passenger car applications, which see significantly higher temperatures than would normally be encountered on a diesel engine. Diesel engines do have one characteristic that makes the

application of NO_x/O₂ sensors more difficult. Soot in diesel exhaust can cause fouling of the NO_x/O₂ sensor damaging its performance. However this issue can be addressed through the application of a catalyzed diesel particulate filter (CDPF) in front of the sensor. The CDPF then provides a protection for the sensor from PM while not hindering its operation. Since the NO_x adsorber is expected to be located downstream of a CDPF in each of the potential technology scenarios we have considered this solution to the issue of PM sooting is readily addressed.

The catalyst can, the metal frame that holds the catalyst substrates in place and in the exhaust system, is a well developed technology in its own right. The catalyst can must be able to secure the catalyst substrates while not chipping or cracking the substrates ceramic material. Further, in the system described in Figure III.A-4, the can must also partition the catalysts into two or more regions. While this is a departure from the way today's three-way catalysts are made, it is not a significant technical challenge when compared to the complex internal geometries of some muffler designs. Corrosion and weld durability are two other important considerations in can design. Advances in material science and manufacturing processes being made for gasoline catalysts designs to meet the stringent Tier 2 standards are expected address these issues.

Fuel is metered into a modern gasoline engine with relatively low pressure pulse-width-modulated fuel injection valves. These valves are designed to cycle well over a million times over the life of a vehicle while continuing to accurately meter fuel. Applying this technology to provide diesel fuel as a reductant for a NO_x adsorber system is a relatively straightforward extension of the technology. A NO_x adsorber system would expect to cycle far fewer times over its life when compared to the current long life of gasoline injectors. However, these gasoline fuel injectors designed to meter fuel into the relatively cool intake of a car can not be directly applied to the exhaust of a diesel engine. In the testing done at NVFEL, a similar valve design was used that had been modified in material properties to allow application in the exhaust of an engine. Thus while benefitting from the extensive experience with gasoline based injectors a designer can, in a relatively straightforward manner, improve the characteristics of the injector to allow application for exhaust reductant regeneration.

The NO_x adsorber system we describe in Figure III.A-4 requires a means to partition the exhaust during regeneration and to control the relative amounts of exhaust flow between two or more regions of the exhaust system. Modern diesel engines already employ a valve designed to carry out this very task. Most modern turbochargers employ a wastegate valve that allows some amount of the exhaust flow to bypass the exhaust turbine in order to control maximum engine boost and limit turbocharger speed. These valves can be designed to be proportional, bypassing a specific fraction of the exhaust flow in order to track a specified boost pressure for the system. Turbocharger wastegate valves applied to heavy-duty diesel engines typically last the life of the engine in spite of the extremely harsh environment within the turbocharger. This same valve approach could be applied in order to accomplish the flow diversion required for diesel NO_x

adsorber regeneration and desulfation. Since temperatures will be typically cooler at the NO_x adsorber compared to the inlet to the exhaust turbine on a turbocharger, the control valve would be expected to be equally reliable when applied in this application.

Toyota has announced its intention to manufacture a CDPF/NO_x adsorber based catalyst system (called Diesel Particulate NO_x Reduction (DPNR)) for application to diesel trucks for the 2003 model year. Schematics of Toyota's prototype suggest that they are applying a wastegate type valve to accomplish flow diversion.⁵⁹ Also the catalyst can has been designed so that the exhaust flow-path can be redirected during the NO_x regeneration step.⁶⁰ Toyota's intent to introduce this type of system in such a short time frame indicates that the technologies needed to apply the NO_x adsorber catalyst are likely to be extensions of existing technologies with which Toyota is already well familiar.

Therefore, the system components needed to implement a NO_x adsorber catalyst system reflect relatively straight-forward extensions of existing automotive hardware which has already demonstrated long life and high levels of reliability.

(b) NO_x Adsorber Catalyst Durability

In many ways a NO_x adsorber like other motor vehicle catalysts, acts like a small chemical process plant. It has specific chemical processes that it promotes under specific conditions with different elements of the catalyst materials. There is often an important sequence to the needed reactions and a need to match process rates in order to keep this sequence of reactions going. Because of this need to promote specific reactions under the right conditions early catalysts were often easily damaged. This damage prevents or slows one or more the reactions causing a loss in emission control.

For example, contaminants from engine oil, like phosphorous or zinc, could attach to catalysts sites partially blocking the site from the exhaust constituents and slowing reactions. Similarly, lead added to gasoline in order to increase octane levels bonds to the catalyst sites causing poisoning as well. Likewise, sulfur which occurs naturally in petroleum products like gasoline and diesel fuel can poison many catalyst functions preventing or slowing the desired reactions. High exhaust temperatures experienced under some driving conditions can cause the catalyst materials to sinter (thermally degrade) decreasing the surface area available for reactions to decrease.

All of these problems have been addressed over time for the gasoline three-way catalysts, resulting in the high efficiency and long life durability now typical of modern vehicles. In order to accomplish this changes were made to fuels and oils used in vehicles (e.g., lead additives banned from gasoline, sulfur levels reduced in gasoline distillates, specific oil formulations for

aftertreatment equipped cars), and advances in catalysts designs were needed to promote sintering resistant catalyst formulations with high precious metal dispersion.

The wealth of experience gained and technological advancements made over the last 30 years of gasoline catalyst development can now be applied to the development of the NO_x adsorber catalyst. The NO_x adsorber is itself an incremental advancement from current three-way catalyst technology. It adds one important additional component not currently used on three-way catalysts, NO_x storage catalyst sites. The NO_x storage sites (normally alkali or alkaline earth metals) allow the catalyst to store NO_x emissions with extremely high efficiency under the lean burn conditions typical of the diesel exhaust. It also adds a new durability concern due to sulfur storage on the catalyst.

This section will explore the durability issues of the NO_x adsorber catalyst applied to diesel vehicles. It describes the effect of sulfur in diesel fuel on catalyst performance, the methods to remove the sulfur from the catalyst through active control processes, and the implications for durability of these methods. It then discusses these durability issues relative to similar issues for existing gasoline three-way catalysts and the engineering paths to solve these issues. This discussion shows that the NO_x adsorber is an incremental improvement upon the existing three-way catalyst, with many of the same solutions for the expected durability issues.

(b.1) Sulfur Poisoning of the NO_x Storage Sites

The NO_x adsorber technology is extremely efficient at storing NO_x as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SO_x and NO_x, the SO₂ present in the exhaust is also stored on the catalyst surface as a sulfate. The sulfate compound that is formed is significantly more stable than the nitrate compound and is typically not released during the NO_x release and reduction step (NO_x regeneration step). Since the NO_x adsorber is virtually 100 percent effective at capturing SO₂ in the adsorber bed, sulfate compounds quickly occupy the NO_x storage sites on the catalyst thereby reducing and eventually rendering the catalyst ineffective for NO_x reduction (poisoning the catalyst).

Figure III.A-12 shows the effect of sulfur poisoning of a NO_x adsorber catalyst as reported by the DOE DECSE program. The graph shows the NO_x adsorber efficiency versus exhaust inlet temperature under steady-state conditions for a diesel engine based system. The three dashed lines that overlap each other show the NO_x conversion efficiency of the catalyst when sulfur has been removed from the catalyst. The three solid lines show the effect of sulfur poisoning on the catalyst at three different fuel sulfur levels over different periods of extended aging (up to 250 hours). From the figure, it can be seen that even with three ppm sulfur fuel a significant loss in NO_x efficiency can occur in as little as 250 hours. Further, it can be seen that quite severe sulfur poisoning can occur with elevated fuel sulfur levels. Catalyst performance

was degraded by more than 70 percent over only 150 hours of operation when 30 ppm sulfur fuel was used.⁶¹

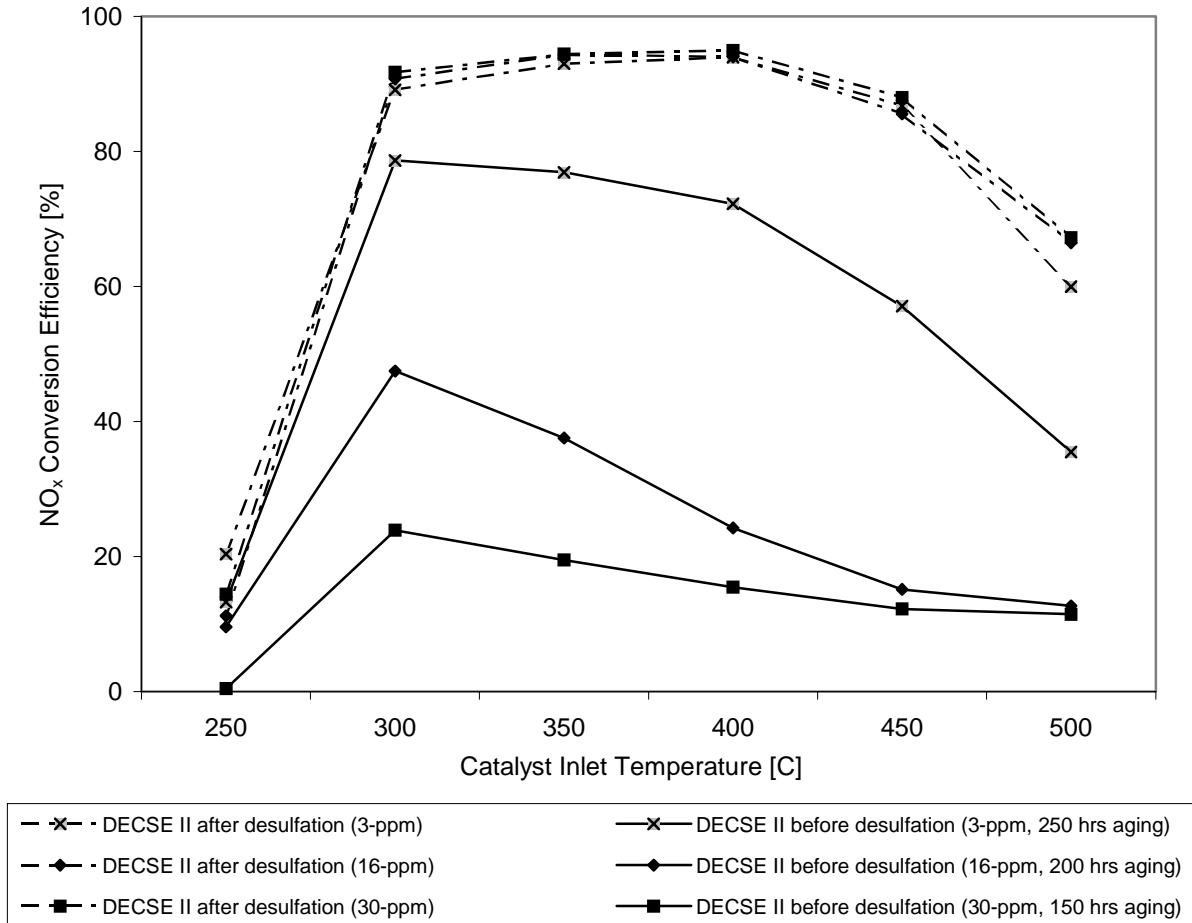


Figure III.A-12. Comparison of NOx Conversion Efficiency before and after Desulfation

The DECSE researchers drew three important conclusions from Figure III.A-12:

- Fuel sulfur, even at very low levels like three ppm, can limit the performance of the NOx adsorber catalyst significantly.
- Higher fuel sulfur levels, like 30 ppm, dramatically increase the poisoning rate, further limiting NOx adsorber performance.
- Most importantly though, the figure shows that if the sulfur can be removed from the catalyst through a desulfation (or desulfurization) event, the NOx adsorber can provide high NOx control even after exposure to sulfur in diesel fuel. This is

evidenced by the sequence of the data presented in the figure. The three high conversion efficiency lines show the NO_x conversion efficiencies after a desulfation event which was preceded by the sulfur poisoning and degradation shown in the solid lines.

The increase in sulfur poisoning rate is important to understand in order to look at the means to overcome the dramatic sulfur poisoning shown here. Sulfur accumulates in the NO_x storage sites preventing their use for NO_x storage. In other words, they decrease the storage volume of the catalyst. The rate at which sulfur fills NO_x storage sites is expected to be directly proportional to the amount of sulfur that enters the catalyst. Therefore, for a doubling in fuel sulfur levels a corresponding doubling in the SO_x poisoning rate would be predicted. In the case of the two most commonly discussed fuel sulfur levels, our proposed 15 ppm sulfur cap with an expected in use average less than 10 ppm and a 50 ppm sulfur cap with a regulated average of 30 ppm, the difference in average sulfur levels would indicate at least a three-fold increase in sulfur poisoning rate (<10 versus 30).

The design of a NO_x adsorber will need to address accommodating an expected volume of sulfur before experiencing unacceptable penalties in either lost NO_x control efficiency or increased fuel consumption due to more frequent NO_x regenerations. The amount of operation allowed before that limit is realized for a specific adsorber design will be inversely proportional to fuel sulfur quantity. In the theoretical case of zero sulfur, the period of time before the sulfur poisoning degraded performance excessively would be infinite. For a more practical fuel sulfur level like the <10 ppm average expected with a 15 ppm fuel sulfur cap the period of operation before unacceptable poisoning levels have been reached is expected to be less than 40 hours (with today's NO_x adsorber formulations).⁶² In the case of a 30 ppm average fuel sulfur level, this period would be reduced by a factor of three or more.

Future improvements in the NO_x adsorber technology are expected due to its relatively early state of development. Some of these improvements are likely to include improvements in the kinds of materials used in NO_x adsorbers to increase the means and ease of removing stored sulfur from the catalyst bed. However, because the stored sulfate species are inherently more stable than the stored nitrate compounds (from stored NO_x emissions), we expect that future NO_x adsorbers will continue to be poisoned by sulfur in the exhaust. Therefore a separate sulfur release and reduction cycle (desulfation cycle) will always be needed in order to remove the stored sulfur.

(b.2) NO_x Adsorber Desulfation

Numerous test programs have shown that sulfur can be removed from the catalyst surface through a sulfur regeneration step (desulfation step) not dissimilar from the NO_x regeneration function.^{63,64,65,66,67,68} The stored sulfur compounds are removed by exposing the catalyst to hot

and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to 1) conditions for a brief period. Under these conditions, the stored sulfate is released and reduced in the catalyst. This sulfur removal process, called desulfation or desulfurization in this document, can restore the performance of the NO_x adsorber to near new operation.

Most of the information in the public domain on NO_x adsorber desulfation is based upon research done either in controlled bench reactors using synthetic gas compositions or on advanced lean burn gasoline engine vehicles. As outlined above these programs have shown that desulfation of NO_x adsorber catalysts can be accomplished under certain conditions but the work does not directly answer whether NO_x adsorber desulfation is practical for diesel engine exhaust conditions. The DECSE Phase II program answers that question.

Phase II of the DECSE program developed and demonstrated a desulfurization (desulfation) process to restore NO_x conversion efficiency lost to sulfur contamination. The engine used in the testing was a high speed direct injection diesel selected to provide a representative source of diesel exhaust and various exhaust temperature profiles to challenge the emission control devices. The desulfation process developed in the DECSE Phase II program controlled the air to fuel ratio and catalyst inlet temperatures to achieve the high temperatures required to release the sulfur from the device. Air to fuel ratio control was accomplished in the program with exhaust gas recirculation (EGR) and a post injection of fuel to provide additional reductants. (See discussion in section III.A.3.b.iii.a, which describes this approach for NO_x regeneration.) Using this approach the researchers showed that a desulfation procedure could be developed for a diesel engine with the potential to meet in-service engine operating conditions and acceptable driveability conditions. The NO_x efficiency recovery accomplished in DECSE Phase II using this approach is shown in Figure III.A-12, above.

The effectiveness of NO_x adsorber desulfation appears to be closely related to the temperature of the exhaust gases during desulfation, the exhaust chemistry (relative air to fuel ratio), and to the NO_x adsorber catalyst formulation.^{69,70} Lower air to fuel ratios (more available reductant) works to promote the release of sulfur from the surface, promoting faster and more effective desulfation. Figure III.A-13 shows results from Ford testing on NO_x adsorber conversion efficiency with periodic aging and desulfation events in a control flow reactor test.⁷¹ The control flow reactor test uses controlled gas constituents that are meant to represent the potential exhaust gas constituents from a lean burn engine. The solid line with the open triangles labeled "w/o regen" shows the loss of NO_x control over thirteen hours of testing without a desulfation event and with eight ppm sulfur in the test gas (this is roughly equivalent to 240 ppm fuel sulfur, assuming an air to fuel ratio for diesels of 30:1).⁷² From the figure it can be seen that without a desulfation event, sulfur rapidly degrades the performance of the NO_x adsorber catalyst. The remaining two lines show the NO_x adsorber performance with periodic sulfur regeneration events timed at one hour intervals and lasting for 10 minutes (a one hour increment on 240 ppm fuel sulfur would be approximately equivalent to 34 hours of operation on seven

ppm fuel). The desulfation events were identical to the NO_x regeneration events, except that the desulfation events occurred at elevated temperatures. The base NO_x regeneration temperature for the testing was 350°C. The sulfur regeneration, or desulfation, event was conducted at two different gas temperatures of 550°C and 600°C to show the effect of exhaust gas temperature on desulfation effectiveness, and thus NO_x adsorber efficiency. From Figure III.A-13 it can be seen that, for this NO_x adsorber formulation, the NO_x recovery after desulfation is higher for the desulfation event at 600°C than at 550°C.

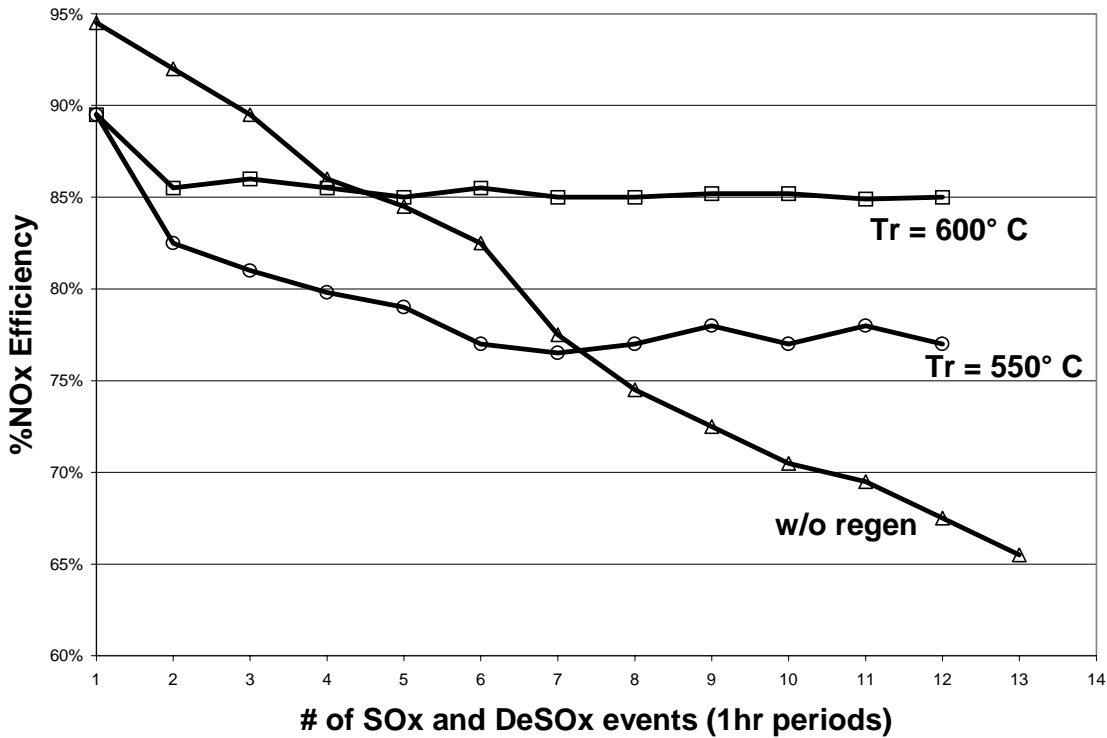


Figure III.A-13. Flow Reactor Testing of a NO_x Adsorber with Periodic Desulfations

As suggested by Figure III.A-13, it is well known that the rate of sulfur release (also called sulfur decomposition) in a NO_x adsorber increases with temperature.^{73 74} However, while elevated temperatures directionally promote more rapid sulfur release, they also can directionally promote sintering of the precious metals in the NO_x adsorber washcoat. The loss of conversion efficiency due to exposure of the catalyst to elevated temperatures is referred to as thermal degradation in this document.

(b.3) Thermal Degradation

The catalytic metals that make up most exhaust emission control technologies, including NO_x adsorbers, are designed to be dispersed throughout the catalyst into as many small catalyst “sites” as possible. By spreading the catalytic metals into many small catalyst sites, rather than into a fewer number large sites, catalyst efficiency is improved. This is because smaller catalyst sites have more surface area per mass, or volume, of catalyst when compared to larger catalyst sites. Since most of the reactions being promoted by the catalyst occur on the surface, increasing surface area increases catalyst availability and thus conversion efficiency. While high dispersion (many small catalyst sites) is in general good for most catalysts, it is even more beneficial to the NO_x adsorber catalyst because of the need for the catalytic metal sites to perform multiple tasks. NO_x adsorber catalysts typically rely on platinum to oxidize NO to NO₂ prior to adsorption of the NO₂ on an adjacent NO_x storage site. Under rich operating conditions, the NO_x is released from the adsorption site, and the adjacent platinum (or platinum + rhodium) catalyst site can serve to reduce the NO_x emissions into N₂ and O₂. High dispersion, combined with NO oxidation, NO_x storage and NO_x reduction catalyst sites being located in close proximity, provide the ideal catalyst design for a NO_x adsorber catalyst. High temperatures, especially under oxidizing conditions, can promote sintering of the platinum and other PGM catalyst sites, permanently decreasing NO_x adsorber performance.

Catalyst sintering is a process by which adjacent catalyst sites can “melt” and regrow into a single larger catalyst site (crystal growth). The single larger catalyst site has less surface area available to promote catalytic activity than the original two or more catalyst sites that were sintered to form it. This loss in surface area decreases the efficiency of the catalyst.⁷⁵ High temperatures promote sintering of platinum catalysts especially under oxidizing conditions.⁷⁶ Therefore, it is important to limit the exposure of platinum based catalysts to high exhaust temperatures especially during periods of lean operation. Consequently, the desire to promote rapid desulfation of the NO_x adsorber catalyst technology by maximizing the desulfation temperature and the need to limit the exposure of the catalyst to the high temperatures that promote catalyst sintering must be carefully balanced. An example of this tradeoff can be seen in Figure III.A-14 below, which shows the NO_x conversion efficiency of three NO_x adsorber catalysts evaluated after extended periods of sulfur poisoning followed by sulfur regeneration periods.⁷⁷ The three catalysts (labeled A, B, and C) are identical in formulation and size but were located at three different positions in the exhaust system of the gasoline direct injection engine used for this testing. Catalyst A was located 1.2 meters from the exhaust manifold, catalyst B 1.8 meters from the exhaust manifold and catalyst C was located 2.5 meters from the exhaust manifold. Locating the catalysts further from the engine lowered the maximum exhaust temperature and thus catalyst bed temperature experienced during the programmed sulfur regeneration cycle. Catalyst A experienced the highest catalyst bed temperature of 800°C, while catalyst C experienced the lowest catalyst bed temperature of 650°C. Catalyst B experienced a maximum catalyst bed temperature of 730°C. Figure III.A-14 shows that an optimum desulfation temperature exists which balances the tradeoffs between rapid sulfur regeneration and thermal degradation (thermal sintering) at high temperatures.

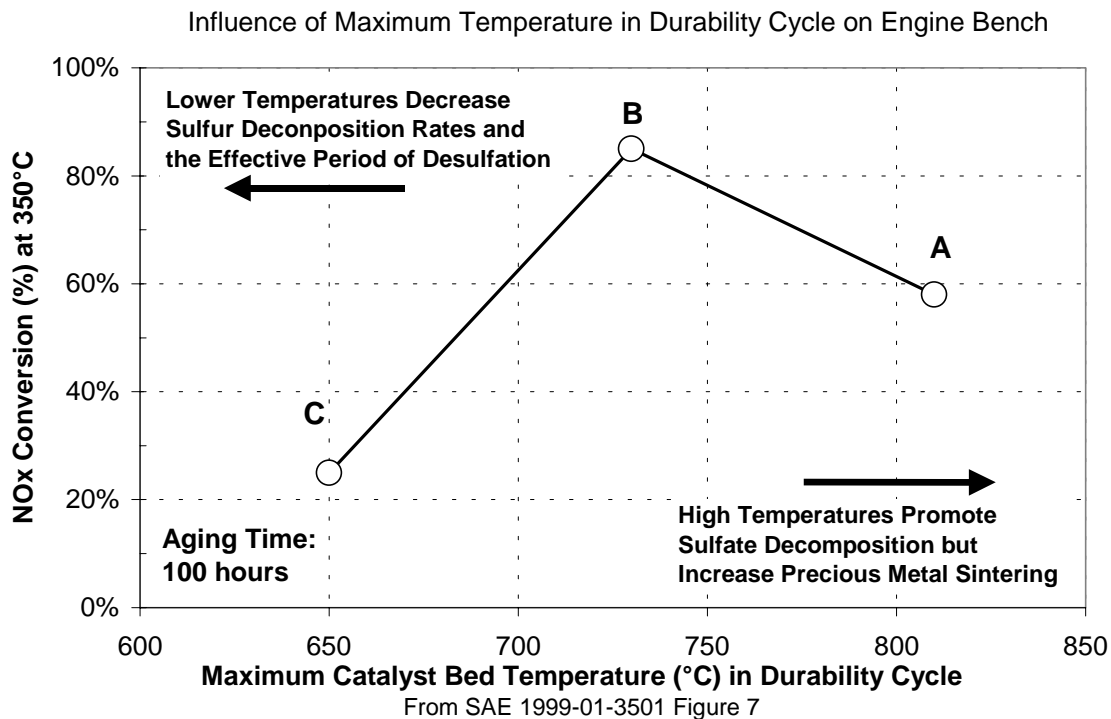


Figure III.A-14. Influence of Maximum Catalyst Bed Temperature During Desulfation

The DECSE Phase II program, in addition to investigating the ability of a diesel engine / NOx adsorber based emission control system to desulfate, provides a preliminary assessment of catalyst durability when exposed to repeated aging and desulfurization cycles. Two sets of tests were completed using two different fuel sulfur levels (three ppm and 78 ppm) to investigate these durability aspects. The first involved a series of aging, performance mapping, desulfurization and performance mapping cycles. An example of this testing is shown below in Figure III.A-15. The graph shows a characteristic “sawtooth” pattern of gradual sulfur poisoning followed by an abrupt improvement in performance after desulfation. The results shown in Figure III.A-15 are for two identical catalysts one operated on 3 ppm sulfur fuel (catalyst S5) and the other operated on 78 ppm sulfur fuel (catalyst S7). For the catalyst operated on 3 ppm sulfur fuel the loss in performance over the ten hours of poisoning is noted to be very gradual. There appears to be little need to desulfate that catalyst at the ten hour interval set in the experiment. In fact it can be seen that in several cases the performance after desulfation is worse than prior to desulfation. This would suggest as discussed above, that the desulfation cycle can itself be damaging to the catalyst. In actual use we would expect that an engine operating on 3 ppm sulfur fuel would not desulfate until well beyond a ten hour interval and would be engineered to better withstand the damage caused by desulfation, as discussed later in this section. For the catalyst operated on 78

ppm sulfur fuel the loss in performance over the ten hour poisoning period is dramatic. In order to ensure continued high performance when operating on 78 ppm sulfur fuel the catalyst would require frequent desulfations. From the figure it can be inferred that the desulfation events would need to be spaced at intervals as short as one to two hours in order to maintain acceptable performance.

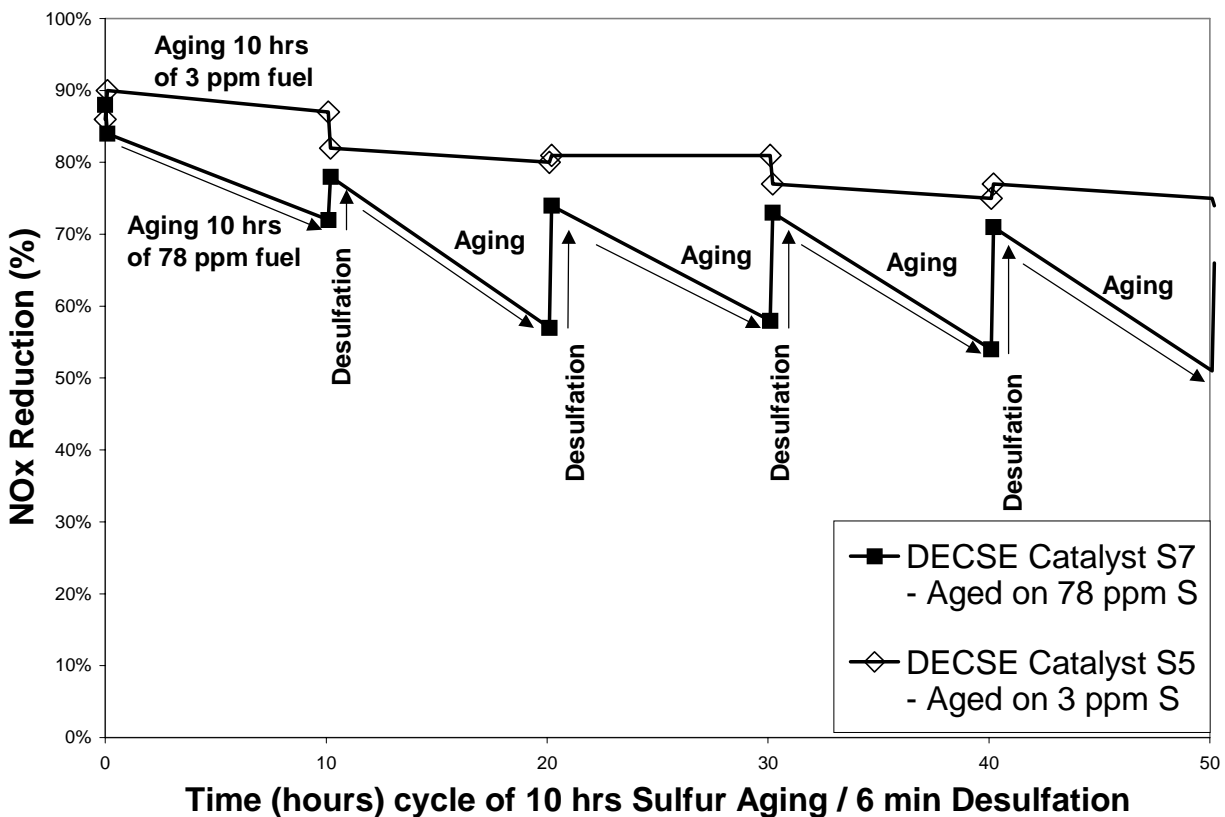


Figure III.A-15. Integrated NOx Conversion Efficiency following Aging and Desulfation

As a follow on to the work shown in Figure III.A-15, the desulfation events were repeated an additional 60 times without sulfur aging between desulfation events. This was done to investigate the possibility of deleterious affects from the desulfation event itself even without additional sulfur poisoning. As can be seen in Figure III.A-16, the investigation did reveal that repeated desulfation events even without additional sulfur aging can cause catalyst deterioration. As described previously, high temperatures can lead to a loss in catalyst efficiency due to thermal degradation (sintering of the catalytic metals). This appears to be the most likely explanation for the loss in catalyst efficiency shown here. For this testing, the catalyst inlet temperature was controlled to approximately 700°C, however the catalyst bed temperatures could have been higher.⁷⁸

Based on the work in DECSE Phase II, the researchers concluded that

- The desulfurization procedure developed has the potential to meet in-service engine operating conditions and to provide acceptable driveability conditions.
- Although aging with 78 ppm sulfur fuel reduced NO_x conversion efficiency more than aging with three ppm sulfur fuel as a result of sulfur contamination, the desulfurization events restored the conversion efficiency to nearly the same level of performance. However, repeatedly exposing the catalyst to the desulfurization procedure developed in the program caused a continued decline in the catalyst's desulfated performance.
- The rate of sulfur contamination during aging with 78 ppm sulfur fuel increased with repeated aging / desulfurization cycles (from 10 percent per ten hours to 18 percent per ten hours). This was not observed with the three ppm sulfur fuel, where the rate of decline during aging was fairly constant at approximately two percent per ten hours.

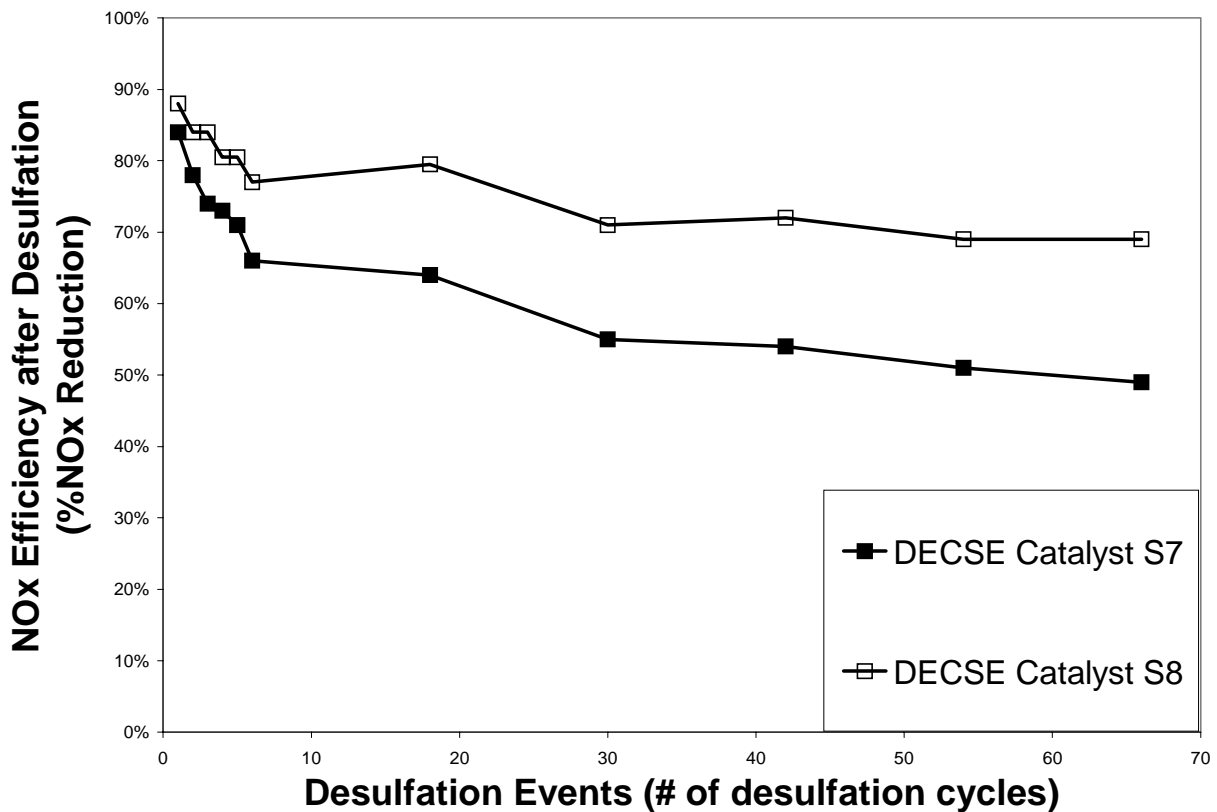


Figure III.A-16. Integrated NO_x Conversion Efficiency after Repeated Desulfation

The data available today on current NO_x adsorber formulations shows clearly that sulfur can be removed from the surface of the NO_x adsorber catalyst. The initial high performance

after a desulfation event is then degraded over time by the presence of sulfur until the next desulfation event. The resulting characteristic NO_x adsorber performance level over time exhibits a saw-tooth pattern with declining performance followed by rapid recovery of performance following desulfation. The rate of this decline increases substantially with higher fuel sulfur levels. In order to ensure a gradual and controllable decline in performance fuel sulfur levels must be minimized. However, even given very low fuel sulfur levels, gradual decline in performance must be periodically overcome. The development experience so far shows that diesel engines can accomplish the required desulfation event. The circumstances that effectively promote rapid desulfation also promote thermal degradation. It will therefore be important to limit thermal degradation.

(b.4) Limiting Thermal Degradation

The issue of thermal degradation of NO_x adsorber catalyst components is similar to the thermal sintering issues faced by light-duty three-way catalysts for vehicles developed to meet current California LEV and future Federal Tier 2 standards using platinum+rhodium (Pt+Rh) catalysts. Initial designs were marked by unacceptable levels of platinum sintering which limited the effectiveness of Pt+Rh catalysts. This problem has been overcome through modifications to the catalyst supports and surface structures that stabilize the precious metals at high temperatures (>900 °C). Stabilization of ceria components using Zirconium (Zr) has pushed the upper temperature limits of ceria migration to well over 1000 °C.^{79, 80} Stabilization components can function in a number of ways. Some are used to “fill” structural vacancies, for example “open” locations within a crystalline lattice, thus strengthening the lattice structure. Such strengthening of crystalline lattice structures is particularly important at high temperatures. Other types of stabilizing components can act as obstructions within a matrix to prevent migration of components, or can enhance the mobility of other molecules or atoms, such as oxygen. An approach to the stabilization of NO_x adsorber catalyst components that is similar to the approaches taken with LEV three-way catalyst designs should help to minimize thermal sintering of components during desulfation.

In many ways, limiting the thermal degradation of the NO_x adsorber catalyst should be easier than for the gasoline three-way catalyst. Typical exhaust gas temperatures for a heavy light-duty gasoline truck (e.g., a Ford Expedition) commonly range from 450°C to more than 800°C during normal operation.⁸¹ A heavy-duty diesel engine in contrast rarely has exhaust gas temperatures in excess of 500°C. Further, even during the desulfation event, exhaust temperatures are expected to be controlled well below 800°C. Therefore the NO_x adsorber when applied to diesel engines is expected to see both lower average temperatures and lower peak temperatures when compared to an equivalent gasoline engine. Once thermal degradation improvements are made to NO_x adsorber catalysts, thermal degradation will reasonably be expected to be less than the level predicted for future Tier 2 gasoline applications.

In addition to the means to improve the thermal stability of the NO_x adsorber by applying many of the same techniques being perfected for the Tier 2 gasoline three-way catalyst applications, an additional possibility exists that the desulfation process itself can be improved to give both high sulfur removal and to limit thermal degradation. The means to do this might include careful control of the maximum temperature during desulfation in order to limit the exposure to high temperatures. Also, improvements in how the regeneration process occurs may provide avenues for improvement. Low air to fuel ratios (high levels of reductant) are known to improve the desulfation process. The high level of reductant may also help to suppress oxygen content in the exhaust to further limit thermal degradation.

Researchers at Ford Scientific Research Labs have investigated NO_x adsorber catalyst desulfation (called DeSO_x in their work) to answer the question: “if a regeneration process (sulfur regeneration) is required periodically, will the high temperatures required for the regeneration have deleterious, irreversible effects on NO_x efficiency?” To explore the issue of NO_x adsorber durability after repeated desulfation events, Ford conducted repeated sequential sulfur poisoning and desulfation cycles with a NO_x adsorber catalyst. The results of their experiment are shown in Figure III.A-17.⁸² As shown in Figure III.A-17, the NO_x adsorber sample underwent more than 90 poisoning and desulfation cycles with 12 hours occurring between the end of one desulfation to the end of the next desulfation without a measurable loss in post-desulfation performance. This testing was done using a laboratory tool called a pulsator, used to study ceramic monolith catalyst samples. The ceramic test samples were heated to between 700°C and 750°C. These results indicate that for some combinations of temperatures and reductant chemistries the NO_x adsorber can be repeatedly desulfated without a significant loss in NO_x reduction efficiency. This work indicates that it is possible to optimize the desulfation process to allow for adequate sulfur removal without a significant decrease in NO_x reduction efficiency.

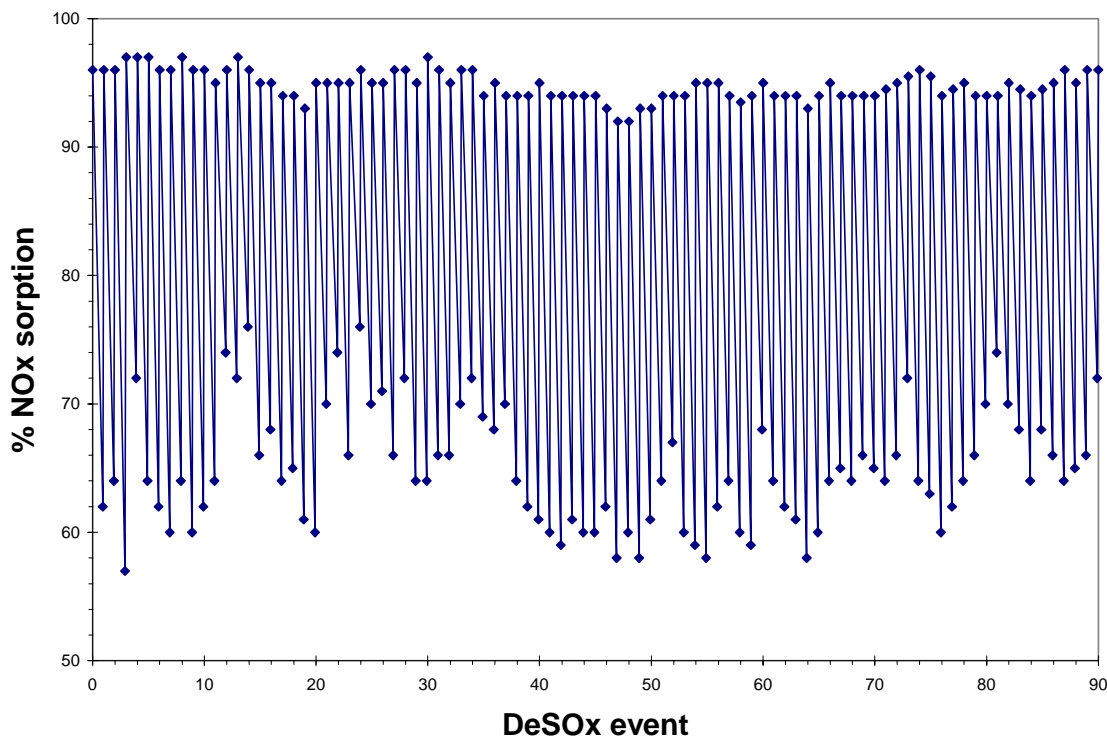


Figure III.A-17. Repeated Sulfur Poisoning and Desulfation on a Bench Pulsator

These results indicate that, with further improvements to the NO_x adsorber catalyst design incorporating the experience gained on gasoline three-way catalysts and continuing improvements in the control of the desulfation, degradation of the NO_x adsorber catalyst with each desulfation event can be limited. However, the expectation remains that there will be some level of deterioration with desulfation that must be managed to ensure long term high efficiency of the NO_x adsorber. This means that the number and frequency of desulfation events must be kept to a minimum. The key to this is to limit the amount of sulfur to which the catalyst is exposed over its life. In this way, the deterioration in performance between desulfation events is controlled at a gradual rate and the period between desulfations can be maximized to limit thermal degradation. There appears to be a general consensus among the technology developers in the emission control industry that, when sulfur levels are controlled with an average level below 10 ppm, the frequency and number of desulfation events will be at a level such that long term durability can be assured. This is evidenced by comments provided on our NPRM. Some examples of those comments are:

1. *The Department (the U.S. Department of Energy) is confident that, assuming a reasonable rate of technology development before 2006, diesel fuel sulfur levels averaging 10 ppm or less will enable emission control devices (NO_x adsorbers and*

CDPFs) to operate effectively over the full useful vehicle life and, therefore, allow the vehicles/engines to meet the future standards (the Phase 2 standards).” - letter from DOE to Bob Perciascepe 6 September 2000, EPA Docket A-99-06 Item IV-G-28.

2. ... the technological challenges posed by the proposed 2007 HDD standards are achievable. .. with the surety of specific standards at a known date, along with a concerted effort by the engine manufacturers and the emission control technology industry, once again we will “make it happen” with technology and integrated systems that meet the standards and are durable. letter from Martin Lassen - Johnson Matthey Catalytic Systems division 19 October 2000, EPA Docket A-99-06 Item IV-G-55.

3. We believe all NOx adsorber development issues have been identified and the technology is proceeding according to schedule. Letter from John Mooney Director, Technology Development and Business Systems Engelhard Corporation to Margo Oge, U.S. EPA 3 October 2000, EPA Docket A-99-06 Item IV-G-38.

EPA agrees and expects this progress is likely to occur along the developmental paths discussed above.

(d) Overall System Durability

NOx emission control with a NOx adsorber catalyst based systems is an extension of the very successful three-way catalyst technology. NOx adsorber technology is most accurately described as incremental and evolutionary with system components that are straightforward extensions of existing technologies. Therefore, the technology benefits substantially from the considerable experience gained over the past 30 years with the highly reliable and durable three-way catalyst systems of today.

The following observations can be made from the data provided in the preceding sections on NOx adsorber durability:

- NOx adsorber catalysts are poisoned by sulfur in diesel fuel, even at fuel sulfur levels as low as three ppm.
- A sulfur regeneration event (desulfation) can restore NOx adsorber performance.
- A diesel engine can produce exhaust conditions that are conducive to desulfation.
- Desulfation events which require high catalyst temperatures can cause sintering of the catalytic metals in the NOx adsorber thereby reducing NOx control efficiency.

- The means exist from the development of gasoline three-way catalysts to improve the NOx adsorber's thermal durability.
- In carefully controlled experiments, NOx adsorbers can be desulfated repeatedly without an unacceptable loss in performance.
- The number and frequency of desulfation events must be limited in order to ensure any gradual thermal degradation over time does not excessively deteriorate the catalyst.

Based on these observations, we are confident that NOx adsorber technology for MY2007 and later engines will be durable over the life of heavy-duty diesel vehicles, provided fuel with a 15 ppm sulfur cap is used. Without the use of this low sulfur fuel, we can no longer be confident that the increased number of desulfation cycles that will be required to address the impact of sulfur on efficiency can be accomplished without unrecoverable thermal degradation and thus loss of NOx adsorber efficiency. Limiting the number and frequency of these deleterious desulfation events through the use of diesel fuel with sulfur content less than 15 ppm allows us to conclude with confidence that NOx adsorber catalysts will be developed that are durable throughout a vehicle's life.

viii. Will NOx Adsorber Desulfation Lead to Undesirable H₂S Emissions?

The desulfation process for a NOx adsorber catalyst is directly analogous to the NOx regeneration process. The stored sulfur emissions are released and reduced over the catalyst before exiting the tailpipe. The final reduction state for the sulfur emissions can be any one of several sulfur products including hydrogen sulfide (H₂S) and sulfur dioxide (SO₂). Hydrogen sulfide has a strong unpleasant odor which is often described as smelling like a rotten egg. For this reason it is preferable to emit the stored sulfur as SO₂ rather than H₂S.

There are several possible ways to control H₂S emissions from an automotive catalyst. For gasoline three-way catalysts which initially had problems with H₂S emissions, the solution has been the inclusion of nickel oxide to the catalyst formulation. Nickel oxide will store sulfur under reducing conditions as nickel sulfide and will release sulfur under oxidizing conditions as SO₂. This storage and release of sulfur emissions in the three-way catalyst has proved effective in controlling H₂S emissions. This approach to controlling sulfur emissions may be possible for NOx adsorber catalysts as well, although because NOx adsorbers store sulfur under lean conditions it may prove to be more difficult to use this approach. A catalyst formulated to store sulfur under both rich and lean conditions would presumably be hindered in its ability to completely remove sulfur under either condition.

Another solution to address H₂S emissions would be the inclusion of a downstream “clean-up” catalyst which could oxidize H₂S emissions, released under rich conditions, to a more desirable sulfur product, namely SO₂. The oxidizing potential for this reaction could come from either oxygen storage elements in the clean-up catalyst or from a second oxygen rich exhaust stream which would join the reducing stream from the desulfating NO_x adsorber prior to entering the clean-up catalyst. The use of a clean-up catalyst is identified as a means to control NMHC emissions during NO_x regeneration as described in sections III.A.3.b.iii and III.A.5. The same approach described in those sections will work well to control H₂S emissions. In our cost analysis described in Chapter V, we have included the cost of a diesel oxidation catalyst in the total system cost in order to address both NMHC emission concerns under NO_x regeneration conditions and H₂S concerns under desulfation conditions.

ix. Can SO_x Traps Protect NO_x Adsorbers from High Sulfur Diesel Fuel?

The preceding discussion of NO_x adsorbers assumes that SO_x (SO₂ and SO₃) emissions will be “trapped” on the surface of the catalyst, effectively poisoning the adsorber and requiring a “desulfation” (sulfur removal event) to recover catalyst efficiency. We believe that, at the 15 ppm cap fuel sulfur level, this strategy will allow effective NO_x control over the life of heavy-duty vehicles. As an alternative to desulfation of the NO_x adsorber itself, some researchers are investigating the use of an adsorber catalyst (SO_x adsorber) designed to preferentially store sulfur emissions in order to serve as a protective catalyst for sulfur sensitive technologies such as NO_x adsorbers. The device would then either require replacement or its own desulfation event in order allow the SO_x adsorber to last for the life of a heavy-duty diesel vehicle.

Replacement of the SO_x adsorber on a periodic basis appears to be a workable solution to the problem of sulfur in diesel fuel only for fuel sulfur levels well below 15 ppm. Analysis provided by Cummins Engine Company estimates that a sulfur trap could store approximately one pound of SO₂ per cubic foot of catalyst volume.⁸³ Based on this assumption an estimate was made of the package volume needed to store one year’s worth of sulfur from diesel fuel for a heavy heavy-duty application that traveled 250,000 miles in one year while averaging seven miles per gallon:

- For five ppm sulfur fuel, the “disposable” SO_x adsorber volume would be 2.5 ft³.
- For 15 ppm sulfur fuel, the “disposable SO_x adsorber volume would be 7.5 ft³.
- For 50 ppm sulfur fuel, the “disposable” SO_x adsorber volume would be 25 ft³.

While it may be possible to imagine packaging a removable SO_x adsorber with a volume of approximately 2.5 cubic feet (~71 liters) for a heavy heavy-duty vehicle, packaging a 25 cubic

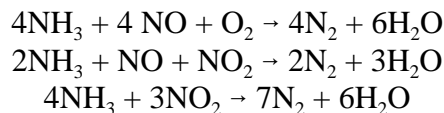
foot (710 liter) catalyst is probably impossible. For comparison typical heavy heavy-duty diesel engine displacements range from 10 to 15 liters in volume.

An alternative approach is to use a SOx adsorber in series with the NOx adsorber and then to either divert the effluent around the NOx adsorber during the SOx adsorber desulfation event or allow the effluent to go through the NOx adsorber under rich conditions which are less conducive to sulfur storage on the catalyst. The first approach of diverting the effluent around the NOx adsorber is theoretically possible, but has several practical limitations. Although SOx adsorbers are highly efficient at capturing sulfur in the exhaust they are not 100 percent effective.⁸⁴ This means that some fugitive sulfur will invariably be deposited on the NOx adsorber catalyst. In other words this approach only defers the needed desulfation event to a later time, although it would allow for less frequent desulfation events which is helpful in controlling thermal degradation. Additionally, diverting the sulfur laden gas around the NOx adsorber adds complexity to the system which is not necessary, since the NOx adsorber itself must also be able to be desulfated. If the sulfur emissions are allowed to travel through the NOx adsorber catalyst (rather than being diverted around) under rich conditions some significant fraction of the sulfur will still be trapped on the NOx adsorber catalyst.⁸⁵ Again, this approach may allow for somewhat less frequent NOx adsorber desulfations but will not eliminate the need for periodic desulfation of the NOx adsorber catalyst.

Based on the eventual need for NOx adsorber desulfation under any of the scenarios described here and the impractical package size of a replacement SOx trap, we believe the only viable approach is to have 15 ppm sulfur diesel fuel.

c. Selective Catalytic Reduction (SCR)

Diesel Selective Catalytic Reduction (SCR) is an adaptation of stationary technology that has been in use for some time. Ammonia (NH₃) is injected into the exhaust upstream of a vanadium/titanium (V₂O₅/TiO₂) catalyst to reduce NOx. The following reactions occur:



The ammonia is typically stored onboard the vehicle as a urea solution ((NH₂)₂CO) since ammonia is hazardous in its raw form. The urea solution is then injected upstream of the catalyst which breaks down the urea into ammonia and carbon dioxide. The ammonia must be injected in proportion to the NOx produced by the engine. If too much ammonia is injected for the amount of NOx present, the excess ammonia can pass unreacted through the SCR catalyst; this is referred to as "ammonia slip." In a mobile transient application, controlling the urea injection to prevent ammonia slippage is key. A diesel oxidation catalyst (DOC) containing platinum can be used

downstream of the SCR system to control ammonia slippage by oxidizing any slipped ammonia to N_2 and H_2O . A DOC can also be used upstream of the SCR system to improve NO_x reduction performance by converting NO to NO₂. Optimum NO_x reduction occurs when the NO_x has a significant NO₂ fraction (note that diesel engine out NO_x typically has only a small fraction of NO₂). Systems that use a DOC to improve cold temperature performance are called “compact SCR” systems due to their relatively small size when compared to conventional SCR systems.

The urea SCR has been developed for stationary applications and is currently being refined for the transient operation found in mobile applications. The reduction efficiency window for this device is similar to the NO_x adsorber, with greater than 80 percent efficiency at exhaust temperatures as low as 250 C.⁸⁶ Testing has shown HD FTP cycle NO_x reductions of 77 percent.⁸⁷ Such efficiencies would allow NO_x levels of 0.5 g/hp-hr to be possible with today’s technology starting with a 2.0 g/hp-hr cooled EGR engine. Lower levels would be possible with engine out emission reductions. Over the NTE zone the SCR has been shown to have 65-99 percent efficiency.⁸⁸

Implementation of SCR poses unique difficulties due to the need to create a new supply chain for the urea. A SCR system consumes urea at a rate proportional to the NO_x emission rate. SCR testing today has shown urea consumption rates ranging from three to six percent of the amount of fuel burned. Therefore, a line haul truck with a 300 gallon fuel tank would need 9 to 18 gallons of urea for every fill-up. Likewise, a large sport utility vehicle (SUV) with a 50 gallon fuel tank would need 1.5 to 3 gallons of urea for every fill-up. If the urea were distributed in liquid form, this would mean an additional on-board tank for urea that would probably have to be replenished at each refueling. Further, without an adequate urea supply onboard, whether by accident or by user intent, the SCR system would become useless, converting none of the NO_x. Since the urea is expected to cost approximately 80 cents per gallon, there would be some incentive for the user not to refill the urea tank.⁸⁹ Since driving performance of the engine is not normally affected by the absence of urea, manufacturers would have to provide incentive for the users to continue refilling the urea tank so that the in-use benefit of the SCR system would be fully realized. What form such a refilling incentive would take is not known. A standardized ammonia distribution format (liquid, solid, etc.), delivery infrastructure, and anti-tampering measures are all issues that would need to be addressed to make this technology viable.

Urea SCR catalysts, like NO_x adsorbers, need low sulfur diesel fuel to achieve high NO_x conversion efficiencies and to control sulfate PM emissions. If low sulfur fuel is required, SCR NO_x control may be possible in some applications by 2007. For a further discussion of SCR system sensitivity to sulfur in diesel fuel, and of its need for low sulfur diesel fuel, refer to section III.A.7. However we believe there are significant barriers to its general use for meeting the 2007 standards.

There would need to be adequate safeguards in place to ensure the urea is used throughout the life of the vehicle since, given the added cost of urea and the fact that urea depletion would not normally affect driveability, there would be an incentive not to refill the urea tank. This could lead to considerable uncertainties regarding the effectiveness of SCR, even if EPA were to promulgate the regulations that likely would be needed to require the regular replenishment of urea. Some would argue that this is the key issue with regard to urea SCR systems, but that this issue could be addressed by designing engines with on-board diagnostic systems utilizing a NO_x sensor that would observe a loss of NO_x control. When observed, the engine would be designed to reduce power gradually until a 50 percent loss of power was realized. This power loss would serve to encourage the user to replenish the urea tank.⁹⁰ While such an approach may be possible, it raises concerns for public safety as poor engine performance could lead to inadequate power for safe merging onto highways and other related driving situations. We remain hesitant to base a national program on such technology when important issues such as driver training on the need to refill the urea tank and the consequences of failure to do so cannot be appropriately controlled. This approach would seem to suggest a need for EPA mandated spot checks of individual vehicles to ensure compliance with the NO_x standard. How such a program would work and the burden that it might place on small business entities was not addressed in the comments. The California Trucking Association has raised concerns about the appropriateness of putting this regulatory burden on truckers when a simpler technology such as a diesel NO_x adsorber was available instead.⁹¹ Without measures similar to these we doubt that users would consistently remember to fill their urea tanks. Since failure to provide urea would lead to a total loss of NO_x control, we would need to model the loss of NO_x control to be expected from an SCR based program.

While SCR systems are capable of limited operation on current sulfur level fuels, their efficiency is reduced at the low temperatures typical of much of diesel engine operation and they run the risk of ammonia slip. Consequently, to achieve the NO_x standard, a SCR system would likely need platinum-containing oxidation catalysts upstream and downstream. The presence of any platinum in the system, whether for conversion of ammonia slip or for conversion of NO to NO₂, would lead to the production of sulfate PM and loss of NO_x reduction efficiency. Therefore, like every exhaust emission control technology discussed so far, the elimination of fuel sulfur is imperative for this technology to be effective.

d. Non-Thermal Plasma Assisted Catalysts

Another approach to NO_x reduction is the non-thermal plasma assisted catalyst. This system works by applying a high voltage across two metal plates in the exhaust stream to form ions that serve as oxidizers. Essentially, the plasma would displace a conventional platinum based oxidation catalyst in function. Once oxidized to NO₂, NO_x can be more readily reduced over a precious metal catalyst or used as an oxidizer, as in CDPFs. A potential drawback of this technology is the high voltage and power requirement. Generation of this power is expected to

entail a two to three percent fuel economy penalty.⁹² We expect that, if and when the non-thermal plasma approach to NO_x control becomes viable, it will also require the use of low sulfur diesel fuel due to its reliance on a precious metal catalyst to reduce the NO₂.⁹³

4. Meeting the NMHC Standard

Meeting the NMHC standards under the lean operating conditions typical of the biggest portion of NO_x adsorber operation should not present any special challenges to diesel manufacturers. Since all of the devices discussed above -- CDPFs, NO_x adsorbers, and SCR -- contain platinum and other precious metals to oxidize NO to NO₂, they are also very efficient oxidizers of hydrocarbons. NMHC reductions of greater than 95 percent have been shown over transient FTP and the SET modes.⁹⁴ Given that typical engine out HC is expected to be in the 0.20 g/bhp-hr range for engines meeting the Phase 1 standards, this level of NMHC reduction will mean that under lean conditions emission levels will be well below the standard.

The NO_x regeneration strategies for the NO_x adsorber technology may prove difficult to control precisely, leading to a possible increase in HC emissions under the rich operating conditions required for NO_x regeneration. Even with precise control of the regeneration cycle, HC slip may prove to be a difficult problem due to the need to regenerate the NO_x adsorber under net rich conditions (excess fuel) rather than the stoichiometric (fuel and air precisely balanced) operating conditions typical of a gasoline three-way catalyst. It seems likely therefore, that in order to meet the HC standards we have set, an additional clean up catalyst may be required. A diesel oxidation catalyst, like those applied historically for HC and partial PM control, can reduce HC emissions (including Toxic HCs) by more than 90 percent.⁹⁵ This amount of additional control along with optimized NO_x regeneration strategies will ensure very low HC emissions.

During the NVFEL NO_x adsorber test evaluation program, we performed extensive testing of a system which included CDPFs, NO_x adsorbers, and a clean-up diesel oxidation catalyst with low platinum loading. As discussed in section III.A.3.b of this RIA, and in more detail in the technical memorandum to the docket detailing this test program, without the use of a clean-up DOC we encountered test conditions which resulted in high HC emissions from the NO_x adsorber regeneration events. As discussed in section III.A.3.b, this complete system, when tested over the hot-start HDDE FTP, resulted in HC emissions of 0.25 g/bp-hr, a 13 percent reduction from the baseline values for the test engine. However, the clean-up DOC we used for this evaluation program had a relatively light precious metal loading (~10 g/ft³) and a relatively low cell density (300 cpsi). Emissions sampling upstream and downstream of this DOC indicated it's oxidation efficiency was less than 60 percent. More effective DOC formulations have been shown to produce greater than an 90 percent reduction in hydrocarbons.⁹⁶ In addition, as discussed in section III.A.3.b, the NVFEL evaluation program did not optimize the hydrocarbon reductant injection strategy in the short time available to the test program. During

the testing we saw opportunities for optimizing the use of the injected diesel fuel to achieve the desired NO_x reduction which we were not able to pursue. With additional time, we would expect to both decrease the HC slip from the emission control system, as well as employ a much more effective DOC, capable of HC reductions on the order of 80 percent. When combined, we expect the NMHC standard will be achieved over the FTP and SET tests, as well as during NTE testing. With a more effective downstream clean-up DOC to control HC slip during the periodic NO_x regeneration event, the HC standard we have set here can be met.

As discussed in section III.A.3.b of this RIA regarding NO_x emissions, the minimum emission sample time provisions for the NTE test have been changed to reflect the potential for short-duration high HC emissions which can occur following a regeneration event. This change to the NTE minimum sample time approach will address any feasibility concerns which could arise because of the short-term increase in HC emissions immediately following a regeneration event, by increasing the sample time to include the time period until the next regeneration. In addition, the NMHC NTE provisions do not apply until the hydrocarbon emission control device (e.g., DOC) has achieved a warmed up exhaust gas temperature of at least 250°C on the outlet of the device. This same provision applies to the NO_x NTE standard. With these additional constraints placed on NTE testing, we conclude the NTE provisions can be achieved.

5. Meeting the Crankcase Emissions Requirements

The most common way to eliminate crankcase emissions has been to vent the blow-by gases into the engine air intake system, so that the gases can be re-combusted. Until today's rulemaking, we have required that crankcase emissions be controlled only on naturally aspirated diesel engines. We have made an exception for turbocharged heavy-duty diesel engines in the past because of concerns regarding fouling that could occur from diesel PM and engine oil, which are included in the crankcase emissions, when routing the crankcase blow-by into the turbocharger and aftercooler. However, this is an environmentally significant exception since most heavy-duty diesel trucks use turbocharged engines, and a single engine can emit over 100 pounds of NO_x, NMHC, and PM from the crankcase over its lifetime. Over the past several years technology has become available which allows us to eliminate the exception for turbocharged diesel engines, as discussed below.

We anticipate that the heavy-duty diesel engine manufacturers will be able to close the crankcase using one of two methods. First, by using closed crankcase filtration systems. We are aware of at least two companies which produce closed crankcase filtration systems for the heavy-duty diesel market today, as described in more detail below.^{97, 98} Second, the blow-by gases could be routed directly into the exhaust system upstream of the emission control equipment. Finally, if the manufacturer chooses not to close the crankcase, the manufacturer must add the emission from the open crankcase ventilation system to the emissions from the engine downstream of any emission control equipment, e.g., the open-crankcase emissions would be added into the FTP

emission results. Thus, the regulatory provision has been written such that if adequate control can be had without “closing” the crankcase then the crankcase can remain “open.”

We expect that in order to meet the stringent tailpipe emission standards set in this rule manufacturers will have to utilize closed crankcase approaches as described here. Closed crankcase filtration systems work by separating oil and particulate matter from the blow-by gases through single or dual stage filtration approaches, routing the blow-by gases into the engine’s intake manifold and returning the filtered oil to the oil sump. Closed crankcases are required for new heavy-duty diesel vehicles in Europe starting in 2000. Oil separation efficiencies in excess of 80 percent have been demonstrated with production ready prototypes of two stage filtration systems after more than 500 hours of testing.^{99 100} By eliminating 80 percent or more of the oil that would normally be vented to the atmosphere, the system works to reduce oil consumption and to eliminate concerns over fouling of the intake system when the gases are routed through the turbocharger. Mercedes-Benz currently utilizes this type of system on virtually all of its heavy-duty diesel engines sold in Europe, and Mercedes-Benz has certified at least one on-highway HDDE in the U.S. equipped with such a system since at least 1999.¹⁰¹

An alternative approach could be to route the blow-by gases into the exhaust system upstream of the CDPF which would be expected to effectively trap and oxidize the engine oil and diesel PM. This approach may require the use of low sulfur engine oil to ensure that oil carried in the blow-by gases does not compromise the performance of the sulfur-sensitive emission control equipment. Further this approach would likely require some means to generate a favorable pressure differential in order to allow the blow-by gases to flow into the exhaust.

Given the available means to control crankcase emissions, we have eliminated this exception.

6. The Complete System

We expect that the technologies described above would be integrated into a complete emission control system optimized for cost, reliability and package size. The engine-out emissions will be balanced with the exhaust emission control package in such a way that the result is the most beneficial from a cost, fuel economy and emissions standpoint. The engine-out exhaust characteristics will also have a role in assisting the exhaust emission control devices used. The NO_x adsorber, for instance, will require periods of oxygen-depleted exhaust flow in order to accomplish NO_x regeneration and to allow for sulfur control using desulfation events. This may be most efficiently done by reducing the air-fuel ratio that the engine is operating under during the regeneration to reduce the oxygen content of the exhaust, or alternatively by partitioning the exhaust flow such that only a small portion of the exhaust flow is used for NO_x regeneration, thereby reducing the amount of oxygen needing to be depleted through fuel addition. Further, it is envisioned that the PM device will be integrated into the exhaust system

upstream of the NO_x reduction device. This placement would allow the PM trap to take advantage of the engine-out NO_x as an oxidant for the particulate, while removing the particulate so that the NO_x exhaust emission control device will not have to deal with large PM deposits which may cause a deterioration in performance. Further it allows the NO_x adsorber to make use of the upstream PM filter as a pre-catalyst to oxidize some NO to NO₂ and to partially oxidize the reductant (diesel fuel or exhaust hydrocarbons) to a more desirable reductant form such as CO before entering the NO_x adsorber. Of course, there is also the possibility of integrating the PM and NO_x exhaust emission control devices into a single unit to replace a muffler and save space (Toyota's DNPR system being an example of this approach).¹⁰² The final component in any of these system configurations is likely to be some form of clean up catalyst which can provide control of HC slip during NO_x regeneration as well as H₂S slip during SO_x regeneration. Particulate free exhaust may also allow for new options in EGR system design to optimize its efficiency.

We expect that the emission reduction efficiency of the exhaust emission control system will vary across the NTE zone as a function of exhaust temperature and space velocity.^m Consequently, to maintain the NTE emission cap, the engine-out emissions would have to be calibrated with exhaust emission control system performance characteristics in mind. This would be accomplished by lowering engine-out emissions where the exhaust emission control system was less efficient, for example by retarding fuel injection timing or increasing the EGR rate. Conversely, where the exhaust emission control system is very efficient at reducing emissions, the engine-out emissions could be tuned for higher emissions and better fuel economy. These trade-offs between engine-out emissions and exhaust emission control system performance characteristics are similar to those of gasoline engines with three-way catalysts in today's light-duty vehicles and can be overcome through similar system based engineering solutions. Managing and optimizing these trade-offs will be crucial to effective implementation of exhaust emission control devices on diesel applications.

In considering how these technologies might be integrated into a complete system, we have carefully considered the safety aspects of the above system. Based on our understanding of these technologies and the fact that we received no substantive comments on safety, we are confident that there are no undue safety concerns associated with the system. Given the proper diesel fuel sulfur level, actual field data have shown that PM traps function properly in-use without plugging. As for the NO_x adsorber system, there is nothing about the expected system that causes concern for safety. Injection of diesel fuel upstream of the NO_x adsorber for the purpose of NO_x regeneration or desulfation presents no safety concern given the low volatility of diesel fuel.

^m The term, "space velocity," is a measure of the volume of exhaust gas that flows through a device.

7. The Need for Low Sulfur Diesel Fuel

In discussing in the preceding sections the technologies that we expect to be needed in order to meet the stringent emissions standards set in this rulemaking, we have described in some detail the impact that sulfur has on these technologies. Because of the importance of the fuel sulfur control portion of this rulemaking, this section will provide a comprehensive overview of the need for low sulfur diesel fuel to enable the technologies capable of achieving the heavy-duty vehicle emission standards.

In order to evaluate the effect of sulfur on diesel exhaust control technologies we identified three key factors which we used to categorize the impact of sulfur in fuel on emission control function. These factors were efficiency, reliability, and fuel economy. Taken together these three factors lead us to believe that diesel fuel sulfur levels of 15 ppm will be required in order to make feasible the heavy-duty vehicle emission standards. Brief summaries of our analyses for each of these factors are provided below.

Efficiency: The efficiency of emission control technologies to reduce harmful pollutants is directly affected by sulfur in diesel fuel. Initial and long term conversion efficiencies for NO_x, HC, CO and diesel PM emissions are significantly reduced by sulfur poisoning of the catalyst. NO_x conversion efficiencies with the NO_x adsorber technology in particular are dramatically reduced in a very short time due to sulfur poisoning of the NO_x storage bed. In addition, total PM control efficiency is adversely impacted by the formation of sulfate PM. As explained in detail in the following sections, all of the advanced NO_x and PM technologies described here have the potential to make significant amounts of sulfate PM under operating conditions typical of heavy-duty vehicles. The formation of sulfate PM is likely to be in excess of the total PM standard for diesel fuel sulfur levels above 15 ppm. Based on the strong negative impact of sulfur on emission control efficiencies for all of the technologies evaluated, we believe that 15 ppm represents an upper threshold for diesel fuel sulfur.

Reliability: Reliability refers to the expectation that emission control technologies must continue to function as required under all operating conditions for the life of the vehicle. As discussed in the following sections, sulfur in diesel fuel can prevent proper operation of both NO_x and PM control technologies. This can lead to permanent loss in emission control effectiveness and even catastrophic failure of the systems. Sulfur in diesel fuel impacts reliability by decreasing catalyst efficiency (poisoning of the catalyst), increasing diesel PM loading on CDPFs, and by negatively impacting system regeneration functions. Among the most serious reliability concerns with sulfur levels greater than 15 ppm are those associated with failure to properly regenerate. In the case of the NO_x adsorber, failure to regenerate will lead to rapid loss of NO_x emission control as a result of sulfur poisoning of the NO_x adsorber bed. In the case of the CDPF, sulfur in the fuel reduces the reliability of the regeneration function. If regeneration does not occur, catastrophic failure of the CDPF could occur. It is only by the availability of very low sulfur diesel fuels that

these technologies become feasible. The analysis given in the following section indicates that diesel fuel sulfur levels of 15 ppm are needed in order to ensure robust operation of the technologies we believe will be needed to meet the standards under the variety of operating conditions anticipated to be experienced in the field.

Fuel Economy: Fuel economy impacts due to sulfur in diesel fuel are associated with both NO_x and PM control technologies. The NO_x adsorber sulfur regeneration cycle (desulfurization or desulfation cycle) can consume significant amounts of fuel unless fuel sulfur levels are very low. The larger the amount of sulfur in diesel fuel, the greater this impact on fuel economy. As sulfur levels increase above 15 ppm, our projected fuel economy impact quickly transitions above one percent and doubles with each doubling of fuel sulfur level. Likewise, CDPF regeneration is inhibited by sulfur in diesel fuel. This leads to increased PM loading in the CDPF and increased work to pump exhaust across this restriction. With very low sulfur diesel fuel, CDPF regeneration can be optimized to give a lower (on average) exhaust backpressure and thus better fuel economy. Thus, for both NO_x and PM technologies the lower the fuel sulfur level the better.

a. Catalyzed Diesel Particulate Filters and the Need for Low Sulfur Fuel

As discussed earlier in this section, un-catalyzed diesel particulate filters require exhaust temperatures in excess of 650°C in order for the collected PM to be oxidized by the oxygen available in diesel exhaust. That temperature threshold for oxidation of PM by exhaust oxygen can be decreased to 450°C through the use of base metal catalytic technologies. Unfortunately, for a broad range of operating conditions diesel exhaust is significantly cooler than 400°C. If oxidation of the trapped PM could be assured to occur at exhaust temperatures lower than 300°C, then diesel particulate filters will be expected to be robust for most applications and operating regimes. The only means that we are aware of to ensure oxidation of PM (regeneration of the CDPF) at such low exhaust temperatures is by using oxidants which are more readily reduced than oxygen. One such oxidant is NO₂.

NO₂ can be produced in diesel exhaust through the oxidation of the nitrogen monoxide (NO), created in the engine combustion process, across a catalyst. The resulting NO₂-rich exhaust is highly oxidizing in nature and can oxidize trapped diesel PM at temperatures as cool as 250°C.¹⁰³ Platinum is the primary catalyst used to promote the oxidation of NO to NO₂. Therefore in order to ensure passive regeneration of the diesel particulate filters, significant amounts of platinum are being used in the wash-coat formulations of advanced catalyzed diesel particulate filters (CDPFs). The use of platinum to promote the oxidation of NO to NO₂ introduces several system vulnerabilities affecting both the durability and the effectiveness of the CDPF when sulfur is present in diesel exhaust. The two primary mechanisms by which sulfur in diesel fuel limits the robustness and effectiveness of CDPFs are inhibition of regeneration (as a result of inhibition of the oxidation of NO to NO₂) and a dramatic loss in total PM control

effectiveness due to the formation of sulfate PM. Unfortunately these two mechanisms tradeoff against one another in the design of CDPFs. Changes to improve the reliability of regeneration by increasing catalyst loadings lead to increased sulfate emissions and thus loss of PM control effectiveness. Conversely, changes to improve PM control by reducing the use of platinum group metals and, therefore, limiting sulfate make leads to less reliable regeneration. In our view, the only means of achieving good PM emission control and reliable operation is to reduce sulfur in diesel fuel to 15 ppm , as shown in the following subsections.

i. Inhibition of CDPF Regeneration Due to Sulfur

The passively regenerating CDPF technologies rely on the generation of a very strong oxidant, NO₂, to ensure that the elemental carbon captured by the CDPF's filtering media is oxidized under normal operating conditions. NO₂ is produced through the oxidation of NO in the exhaust across a platinum catalyst. This oxidation is inhibited by sulfur poisoning of the catalytic metals.¹⁰⁴ This inhibition limits the total amount of NO₂ available for oxidation of the trapped diesel PM, thereby raising the minimum exhaust temperature required to ensure CDPF regeneration. The balance point temperature is the temperature at which PM accumulation matches the PM oxidation rate in a CDPF. In other words, the lowest temperature at which the CDPF would never plug due to PM buildup. Figure III.A-18 shows that going from three ppm sulfur fuel to 30 ppm sulfur fuel significantly increases the balance point of these CDPFsⁿ through inhibition of the NO₂ conversion process.¹⁰⁵ This seemingly small change in balance point temperature (approximately 10 percent) is significant because temperatures in the range shown here are representative of likely exhaust temperatures for many diesel vehicles under normal driving cycles. Were typical exhaust temperatures in excess of 400°C for most engine operating conditions, this change would be less important. Without sufficient NO₂, the amount of PM trapped in the CDPF will continue to increase and can lead to excessive exhaust back pressure, low engine power, and even catastrophic failure of the CDPF itself.

ⁿ CR-DPF in the figure refers to a continuously regenerating diesel particulate filter, CDPF refers to a catalyzed diesel particulate filter. Both devices are nearly functionally identical, and the term CDPF is used for either device in the text.

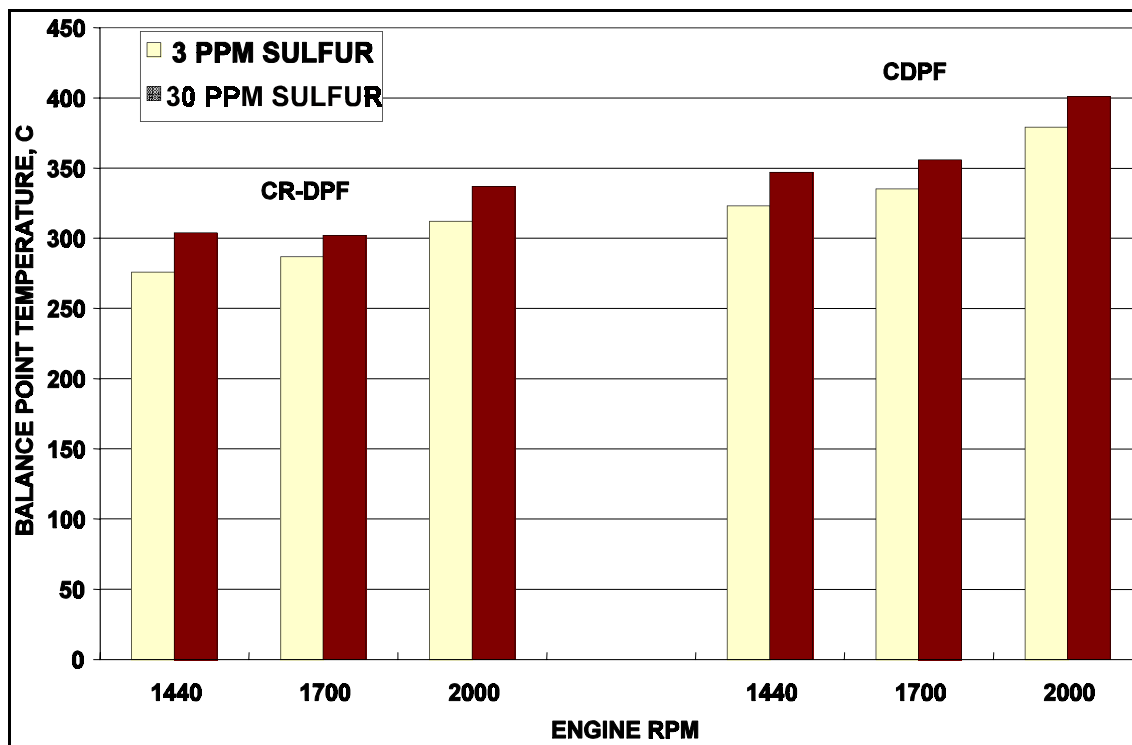


Figure III.A-18. Effect of Fuel Sulfur on Regeneration Temperature

Full field test evaluations and retrofit applications of these catalytic trap technologies are occurring in parts of Europe where low sulfur diesel fuel is already available.^o The experience gained in these field tests helps to clarify the need for low sulfur diesel fuel. In Sweden and some European city centers where below 10 ppm diesel fuel sulfur is readily available, more than 3,000 catalyzed diesel particulate filters have been introduced into retrofit applications without a single failure. Given the large number of vehicles participating in these test programs, the diversity of the vehicle applications which included intercity trains, airport buses, mail trucks, city buses and garbage trucks, and the extended time periods of operation (some vehicles have been operating with traps for more than 5 years and in excess of 300,000 miles), there is a strong indication of the robustness of this technology on 10 ppm low sulfur diesel fuel.¹⁰⁶ The field experience in areas where sulfur is capped at 50 ppm has been less definitive. In regions without extended periods of cold ambient conditions, such as the United Kingdom, field tests on 50 ppm cap low sulfur fuel have also been positive, matching the durability at 10 ppm, although sulfate

^o Through tax incentives 50 ppm cap sulfur fuel is widely available in the United Kingdom and 10 ppm sulfur fuel is available in Sweden and in certain European city centers.

PM emissions are much higher. However, field tests on 50 ppm fuel in Finland, where colder winter conditions are sometimes encountered (similar to many parts of the United States), showed a significant number of failures (~10 percent) due to trap plugging. This 10 percent failure rate has been attributed to insufficient trap regeneration due to fuel sulfur in combination with low ambient temperatures.¹⁰⁷ Other possible reasons for the high failure rate in Finland when contrasted with the Swedish experience appear to be unlikely. The Finnish and Swedish fleets were substantially similar, with both fleets consisting of transit buses powered by Volvo and Scania engines in the 10 to 11 liter range. Further, the buses were operated in city areas and none of the vehicles were operated in northern extremes such as north of the Arctic Circle.¹⁰⁸ Given that the fleets in Sweden and Finland were substantially similar, and given that ambient conditions in Sweden are expected to be similar to those in Finland, we believe that the increased failure rates noted here are due to the higher fuel sulfur level in a 50 ppm cap fuel versus a 10 ppm cap fuel.^p Testing on an even higher fuel sulfur level of 200 ppm was conducted in Denmark on a fleet of 9 vehicles. In less than six months all of the vehicles in the Danish fleet had failed due to trap plugging.¹⁰⁹ The failure of some fraction of the traps to regenerate when operated on fuel with sulfur caps of 50 ppm and 200 ppm is believed to be primarily due to inhibition of the NO to NO₂ conversion as described here. Similarly the increasing frequency of failure with higher fuel sulfur levels is believed to be due to the further suppression of NO₂ formation when higher sulfur level diesel fuel is used.

The failure mechanisms experienced by CDPFs due to low NO₂ availability vary significantly in severity and long term consequences. In the most fundamental sense, the failure is defined as an inability to oxidize the stored PM at a rate fast enough to prevent net accumulation of the PM over time. The excessive accumulation of PM over time blocks the passages through the filtering media, making it more restrictive to exhaust flow. The exhaust pressure upstream of the CDPF must increase in order to continue to force the exhaust through the now more restrictive filter. This increase in exhaust pressure is commonly referred to as increasing “exhaust backpressure” on the engine.

The increased exhaust backpressure represents increased work being done by the engine to force the exhaust gas through the increasingly restrictive CDPF. Unless the CDPF is frequently cleansed of the trapped PM, this increased work can lead to reductions in engine performance and increases in fuel consumption. This loss in performance may be noted by the vehicle operator in terms of poor acceleration and generally poor driveability of the vehicle. This

^p The average temperature in Helsinki, Finland, for the month of January is 21°F. The average temperature in Stockholm, Sweden, for the month of January is 26°F. The average temperature at the University of Michigan in Ann Arbor, Michigan, for the month of January is 24°F. The temperatures reported here are from www.worldclimate.com based upon the Global Historical Climatology Network (GHCN) produced jointly by the National Climatic Data Center and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory (ORNL).

progressive deterioration of engine performance as more and more PM is accumulated in the filter media is often referred to as “trap plugging.” Whether trap plugging occurs, and the speed at which it occurs, will be a function of many variables in addition to the fuel sulfur level; these variables include the vehicle application, its duty cycle, and ambient conditions. However, if the fuel sulfur level is sufficient to prevent CDPF regeneration in some real world conditions experienced, trap plugging could theoretically occur with just one fill-up.⁹ This is not to imply that any time a vehicle is refueled once with high sulfur fuel trap plugging will occur. In fact, we believe the likelihood of a single misfueling event causing failure of the CDPF to be small, because adverse driving conditions (low duty cycle and very cold ambient conditions) would also have to occur while the fuel is in the vehicle. Rather it is important to know that the use of fuel with sulfur levels higher than 15 ppm significantly increases the chances of CDPF failure.

Catastrophic failure of the CDPF can occur when excessive amounts of PM are trapped in the CDPF due to a lack of NO₂ for oxidation. This failure occurs when excessive amounts of trapped PM begin to oxidize at high temperatures (i.e., CDPF regeneration temperatures of >1000°C) leading to a “run-away” combustion of the PM. This can cause temperatures in the filter media to increase in excess of that which can be tolerated by the CDPF itself. For the cordierite material commonly used as the trapping media for CDPFs, the high thermal stresses caused by the high temperatures can cause the material to crack or melt. This can allow significant amounts of the diesel PM to pass through the CDPF without being captured during the remainder of the vehicle’s life. That is, the CDPF is destroyed and PM emission control is lost.

As shown above, sulfur in diesel fuel inhibits NO oxidation leading to increased exhaust backpressure, reduced fuel economy, and compromised reliability. We, therefore, believe that in order to ensure reliable and economical operation over a wide range of expected operating conditions a diesel fuel sulfur level of 15 ppm will be needed. With these very low sulfur levels we believe, as demonstrated by experience in Europe, that CDPFs will prove to be both durable and effective at controlling diesel PM emissions to the very low levels required by this standard.

ii. Loss of PM Control Effectiveness

In addition to inhibiting the oxidation of NO to NO₂, the sulfur dioxide (SO₂) in the exhaust stream is itself oxidized to sulfur trioxide (SO₃) at very high conversion efficiencies, by

⁹ Assuming a 10 liter engine, that a CDPF is plugged when it accumulates 7 g/l of CDPF volume, the CDPF is two times the volume of the engine, the engine emits 0.1 g/hp-hr PM, the CDPF does not regenerate, and a HD engine produces 3.013 hp-hr/mi (from MOBILE6). Then PM is emitted at a rate of 0.1 g/hp-hr times 3.013 hp-hr/mi, or 0.3 g/mi. Given that the CDPF can contain 7g/l times 10 l times 2, or 140 g of PM, then the CDPF will plug in 140 g PM divided by 0.3 g/mi, or 462 miles. HD trucks typically have a cruising range of more than 500 miles, so it is conceivable that the CDPF could plug in as little as one tank of fuel.

the precious metals in the CDPFs. The SO_3 serves as a precursor to the formation of hydrated sulfuric acid ($\text{H}_2\text{SO}_4+\text{H}_2\text{O}$), or sulfate PM, as the exhaust leaves the vehicle tailpipe. Virtually all of the SO_3 is converted to sulfate under dilute exhaust conditions in the atmosphere as well in the dilution tunnel used in heavy-duty engine testing. The sulfate formed in the dilution tunnel is then collected and measured as part of the total PM. Since virtually all sulfur present in diesel fuel is converted to SO_2 , the precursor to SO_3 , as part of the combustion process, the total sulfate PM is directly proportional to the amount of sulfur present in diesel fuel. Therefore, even though CDPFs are very effective at trapping and/or oxidizing the elemental carbon and the SOF portions of the total PM, the overall PM reduction efficiency of CDPFs drops off rapidly with increasing sulfur levels due to the production of sulfate PM (i.e., “sulfate make,” see Figures III.A-1 and III.A-2).

SO_2 oxidation is promoted across a catalyst in a manner very similar to the oxidation of NO, except it is converted at higher rates (Figure III.A-19^r), with peak conversion rates in excess of 50 percent (Table III.A-5).¹¹⁰ The SO_2 oxidation rate for a platinum based oxidation catalyst typical of the type which might be used in conjunction with, or as a washcoat on, a CDPF can vary significantly with exhaust temperature. At the low temperatures typical of some urban driving and the heavy-duty federal test procedure (HD-FTP), the oxidation rate is relatively low, perhaps no higher than ten percent. However at the higher temperatures that might be more typical of non-urban highway driving conditions and the supplemental emission test (SET, also called the EURO III or 13 mode test), the oxidation rate may increase to 50 percent or more. These high levels of sulfate make across the catalyst are in contrast to the very low SO_2 oxidation rate typical of diesel engines (less than 2 percent). This variation in expected diesel exhaust temperatures means that there will be a corresponding range of sulfate production expected across a CDPF.

^r In Figure III.A-19, the legend shows values of $42,000 \text{ hr}^{-1}$ and $373,000 \text{ hr}^{-1}$. These values refer to “space velocity,” which is a measure of the volume of exhaust gas that flows through a device; these can be taken to mean “low flow rate” at $42,000 \text{ hr}^{-1}$ and “high flow rate” at $373,000 \text{ hr}^{-1}$.

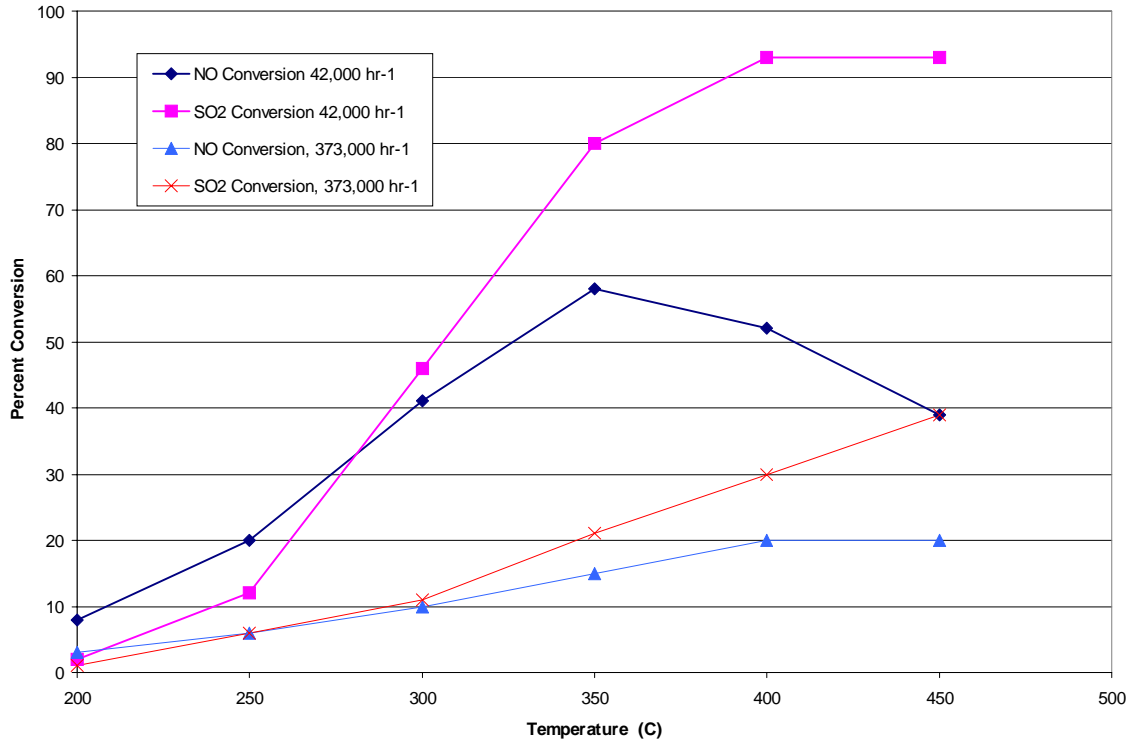


Figure III.A-19. NO and SO₂ Conversion Rates Over Platinum

Table III.A-5. SO₂ Oxidation Rates for a Platinum Oxidation Catalyst at the Indicated Catalyst Inlet Temperatures

<i>Catalyst Temperature</i>	<i>SO₂ Oxidation* Rate</i>	<i>Operation Represented</i>
200°C	1-3%	Idle, very low load
250°C	4-11%	HD-FTP some Urban Driving
300°C	10-45%	EURO III some Rural Driving
350°C	20-80%	EURO III some Rural Driving
400°C	30-90%	EURO III some Rural Driving
450°C	40-90%	Peak Torque and Rated Conditions

* Range in oxidation rates accounts for variations in exhaust flow through the CDPF, at very high flow rates SO₂ oxidation is minimized and at low flow rates SO₂ oxidation is maximized.

The US Department of Energy in cooperation with industry conducted a study entitled Diesel Emission Control Sulfur Effects (DECSE) to provide insight into the relationship between advanced emission control technologies and diesel fuel sulfur levels. Interim report number four of this program gives the total PM emissions from a heavy-duty diesel engine operated with a CDPF on several different fuel sulfur levels. A straight line fit through this data is presented in Table III.A-6 below showing the expected total direct PM emissions from a heavy-duty diesel engine on the supplemental steady state test cycle.^s

^s Note that direct emissions are those pollutants emitted directly from the engine or from the tailpipe depending on the context in which the term is used, and indirect emissions are those pollutants formed in the atmosphere through the combination of direct emissions and atmospheric constituents.

Table III.A-6. Estimated PM Emissions from a Heavy-Duty Diesel Engine at the Indicated Average Fuel Sulfur Levels

<i>Fuel Sulfur [ppm]</i>	<i>Supplemental Steady State*</i>	
	<i>Tailpipe PM [g/bhp-hr]</i>	<i>Total PM Increase Relative to 3 ppm Sulfur Test Point</i>
3	0.003	--
7*	0.006	100 %
15*	0.009	200 %
30	0.017	470 %
150	0.071	2300 %

* The PM emissions at these sulfur levels are estimated based on a straight-line fit to the DECSE program data; PM emissions at other sulfur levels are actual DECSE data. ¹¹¹

Table III.A-6 makes it clear that there are significant PM emission reductions possible with the application of CDPFs and low sulfur diesel fuel. At the observed sulfate PM conversion rates, the DECSE program results show that the PM standard is feasible for CDPF-equipped engines operated on fuel with a sulfur level at or below 15 ppm. The results also show that CDPF control effectiveness is rapidly degraded at higher diesel fuel sulfur levels due to the high sulfate PM make observed with this technology. It is clear that PM reduction efficiencies are limited by sulfur in diesel fuel and that, in order to realize the PM emissions benefits sought in this rule, diesel fuel sulfur levels must be very low.

iii. Increased Maintenance Cost for Catalyzed Diesel Particulate Filters Due to Sulfur

In addition to the direct performance and durability concerns caused by sulfur in diesel fuel, it is also known that sulfur can lead to increased maintenance costs, shortened maintenance intervals, and poorer fuel economy for CDPFs. CDPFs are highly effective at capturing the inorganic ash produced from metallic additives in engine oil. This ash is accumulated in the CDPF and is not removed through oxidation, unlike the trapped carbonaceous PM. Periodically the ash must be removed by mechanical cleaning of the CDPF with compressed air or water. This maintenance step is anticipated to occur on intervals of well over one hundred thousand miles. However, sulfur in diesel fuel increases this ash accumulation rate through the formation of metallic sulfates in the CDPF, which increases both the size and mass of the trapped ash. By increasing the ash accumulation rate the sulfur shortens the time interval between the required maintenance of the CDPF and negatively impacts fuel economy.

b. Diesel NO_x Catalysts and the Need for Low Sulfur Fuel

All of the NO_x aftertreatment technologies discussed previously in chapter III are expected to utilize platinum to oxidize NO to NO₂ to improve the NO_x reduction efficiency of the catalysts at low temperatures or as in the case of the NO_x adsorber, as an essential part of the process of NO_x storage. This reliance on NO₂ as an integral part of the reduction process means that the NO_x aftertreatment technologies, like the PM aftertreatment technologies, will have problems with sulfur in diesel fuel. In addition NO_x adsorbers have the added constraint that the adsorption function itself is blocked by the presence of sulfur. These limitations due to sulfur in the fuel affect both overall performance of the technologies and, in fact, the very feasibility of the NO_x adsorber technology.

i. Sulfur Poisoning (Sulfate Storage) on NO_x Adsorbers

The NO_x adsorber technology relies on the ability of the catalyst to store NO_x as a nitrate on the surface of the catalyst, or adsorber (storage) bed, during lean operation. Because of the similarities in chemical properties of SO_x and NO_x, the SO₂ present in the exhaust is also stored by the catalyst surface as a sulfate. The sulfate compound that is formed is significantly more stable than the nitrate compound and is typically not released and reduced during the NO_x release and reduction step. Since the NO_x adsorber is highly effective at capturing SO₂ in the adsorber bed, the poisoning of the catalyst occurs rapidly. As a result, sulfate compounds quickly occupy all of the NO_x storage sites on the catalyst thereby rendering the catalyst ineffective for NO_x reduction (poisoning the catalyst). Figure III.A-20 clearly illustrates this effect at 3, 16, and 30 ppm fuel sulfur levels.¹¹²

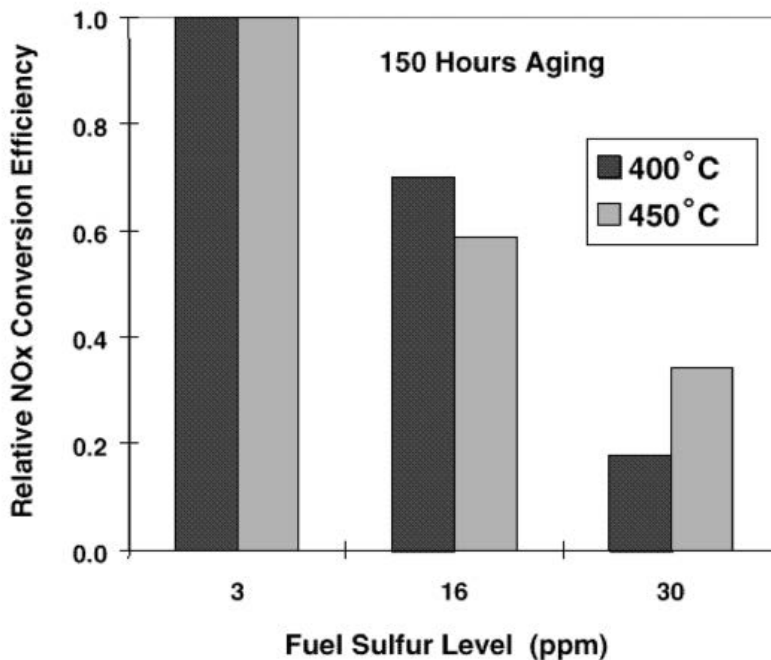


Figure III.A-20. Diesel Fuel Sulfur Effect on NOx Adsorber Performance after 150 hours

The stored sulfur compounds can be removed by exposing the catalyst to hot ($>650^{\circ}\text{C}$) and rich (air-fuel ratio below the stoichiometric ratio of 14.5 to one) conditions for a brief period.¹¹³ Under these conditions, the stored sulfate is released and reduced in the catalyst.^{114 115} While research to date on this procedure has been very favorable with regards to sulfur removal from the catalyst, it has revealed a related vulnerability of the NOx adsorber catalyst. Under the high temperatures used for desulfation, the metals that make up the storage bed can change in physical structure. This leads to lower precious metal dispersion, or “metal sintering,” (a less even distribution of the catalyst sites) reducing the effectiveness of the catalyst.¹¹⁶ This degradation of catalyst efficiency due to high temperatures is often referred to as thermal degradation. Thermal degradation is known to be a cumulative effect. That is, with each excursion to high temperature operation, some additional degradation of the catalyst occurs.

One of the best ways to limit thermal degradation is by limiting the accumulated number of desulfation events over the life of the vehicle. Since the period of time between desulfation events is expected to be determined by the amount of sulfur accumulated on the catalyst (the higher the sulfur accumulation rate, the shorter the period between desulfation events) the desulfation frequency is expected to be proportional to the fuel sulfur level. In other words for each doubling in the average fuel sulfur level, the frequency and accumulated number of desulfation events are expected to double. We believe, therefore, that the diesel fuel sulfur level

must be set as low as possible in order to limit the frequency and duration of desulfation events. Without control of fuel sulfur levels below 15 ppm, we can no longer conclude with sufficient confidence that sulfur poisoning can be controlled without unrecoverable thermal degradation. Some would argue that the NOx adsorber technology could meet the NOx standard using diesel fuel with a 30 ppm average sulfur level. This would imply that the NOx adsorber could tolerate more than a three to four fold increase in desulfation frequency (when compared to an expected fuel sulfur level of 7 to 10 ppm with a 15 ppm cap) without any increase in thermal degradation. This conclusion is inconsistent with our understanding of the technology that, with each desulfation event, some thermal degradation occurs. Therefore, we believe that diesel fuel sulfur levels must be at or below 15 ppm in order to limit the number and frequency of desulfation events. Limiting the number and frequency of desulfation events will limit thermal degradation and, thus, enable the NOx adsorber technology to meet the NOx standard. For additional discussion of thermal degradation refer to the previous discussion in section III.A.3.b.vii on NOx adsorber durability.

Sulfur in diesel fuel for NOx adsorber equipped engines will also have an adverse effect on fuel economy. The desulfation event requires controlled operation under hot and net fuel rich exhaust conditions. These conditions, which are not part of a normal diesel engine operating cycle, can be created through the addition of excess fuel to the exhaust. This addition of excess fuel causes an increase in fuel consumption. We have developed a spreadsheet model that estimates the frequency of desulfation cycles from published data and then estimates the fuel economy impact from this event.¹¹⁷ Table III.A-7 shows the estimated fuel economy impact for desulfation of a NOx adsorber at different fuel sulfur levels assuming a desired 90 percent NOx conversion efficiency. The estimates in the table are based on assumed average fuel sulfur levels associated with different sulfur level caps. Note that, although we can estimate the fuel consumption penalty of operation on diesel fuel sulfur levels higher than 15 ppm, this analysis does not consider the higher degree of thermal degradation due to the more frequent desulfation events which are required for operation on these higher sulfur levels.

Table III.A-7. Estimated Fuel Economy Impact from Desulfation of a 90 Percent Efficient NOx Adsorber

<i>Fuel Sulfur Cap [ppm]</i>	<i>Average Fuel Sulfur [ppm]</i>	<i>Fuel Economy Penalty [%]</i>
500	350	27
50	30	2
25	15	1
15	7	< 1
5	2	<<< 1

The table shows that the fuel economy penalty associated with sulfur in diesel fuel is noticeable even at average sulfur levels as low as 15 ppm and increases rapidly with higher sulfur levels. It also shows that the 15 ppm sulfur cap will be expected to result in a fuel economy impact of less than one percent absent other changes in engine design.

As a consequence of requiring desulfation to occur before the NOx adsorber catalyst degrades to a level below 90 percent, the fuel economy impacts at higher sulfur levels described here are substantial. Therefore it would be logical to consider the possibility of allowing further degradations in NOx performance (below 90 percent) before desulfation in order to reduce this fuel economy impact. Recent results from industry contradict that position, however, indicating that when deep poisoning of the catalyst occurs due to higher fuel sulfur levels (or presumably extend periods of poisoning without desulfation) the ability of the catalyst to recover from the sulfur poisoning is compromised.¹¹⁸ This data from a gasoline direct injection application indicates that desulfation events sequenced on a fixed interval with only minimal poisoning allowed for full recovery of NOx performance (eight ppm sulfur fuel, regenerated on a fixed driving cycle with 32,000 km of vehicle operation). These good results are contrasted with performance on 30 ppm sulfur fuel in which NOx adsorber desulfation occurred on the same fixed interval (thus allowing greater levels of poisoning before desulfation). For this case NOx control performance was never fully recovered at each desulfation step and, therefore, continued to gradually decrease over time from an initial efficiency of 95 percent to 80 percent over the same 32,000 km of vehicle operation.

Future improvements in the NOx adsorber technology are expected and needed if the technology is to provide the environmental benefits we have projected today. Some of these improvements are likely to include improvements in the means and ease to remove stored sulfur from the catalyst bed. However, because the stored sulfate species are inherently more stable

than the stored nitrate compounds (from stored NO_x emissions), we expect that a separate release and reduction cycle (desulfurization cycle) will always be needed in order to remove the stored sulfur. Therefore, we believe that fuel with a sulfur level at or below 15 ppm sulfur will be necessary in order to control thermal degradation of the NO_x adsorber catalyst and to limit the fuel economy impact of sulfur in diesel fuel.

ii. *Particulate Sulfate Production for NO_x Control Technologies*

The NO_x adsorber technology relies on a platinum based oxidation function in order to ensure high NO_x control efficiencies. As discussed more fully in section III.A.7.a, platinum based oxidation catalysts form sulfate PM from sulfur in the exhaust gases significantly increasing PM emissions when sulfur is present in the exhaust stream. The NO_x adsorber technology relies on the oxidation function to convert NO to NO₂ over the catalyst bed. For the NO_x adsorber this is a fundamental step prior to the storage of NO₂ in the catalyst bed as a nitrate. Without this oxidation function the catalyst will only trap that small portion of NO_x emissions from a diesel engine which is NO₂. This would reduce the NO_x adsorber effectiveness for NO_x reduction from in excess of 90 percent to something well below 20 percent. The NO_x adsorber relies on platinum to provide this oxidation function due to the need for high NO oxidation rates under the relatively cool exhaust temperatures typical of diesel engines. Because of this fundamental need for a catalytic oxidation function, the NO_x adsorber inherently forms sulfate PM when sulfur is present in diesel fuel, since sulfur in fuel invariably leads to sulfur in the exhaust stream.

The Compact-SCR technology, like the NO_x adsorber technology, uses an oxidation catalyst to promote the oxidation of NO to NO₂ at the low temperatures typical of much of diesel engine operation. As discussed above, there are substantial questions regarding the ability of SCR systems to be implemented successfully to meet the requirements finalized today. By converting a portion of the NO_x emissions to NO₂ upstream of the ammonia SCR reduction catalyst, the overall NO_x reductions are improved significantly at low temperatures. Without this oxidation function, low temperature SCR NO_x effectiveness is dramatically reduced making compliance with the NO_x standard impossible. As discussed previously in section III.A.7, platinum is known to be a good catalyst to promote NO oxidation, even at low temperatures.¹ Therefore, future Compact-SCR systems would need to rely on a platinum oxidation catalyst in order to provide the required NO_x emission control. This use of an oxidation catalyst in order to enable good NO_x control means that Compact SCR systems will produce significant amounts of sulfate PM when operated on anything but the lowest fuel sulfur levels due to the oxidation of SO₂ to sulfate PM promoted by the oxidation catalyst.

¹ Platinum group metals include platinum, palladium, rhodium, and other precious metals.

Without the oxidation catalyst promoted conversion of NO to NO₂, neither of these NOx control technologies can meet the NOx standard set here. Therefore each of these technologies will require low sulfur diesel fuel to control the sulfate PM emissions inherent in the use of oxidation catalysts. The NOx adsorber technology may be able to limit its impact on sulfate PM emissions by releasing stored sulfur as SO₂ under rich operating conditions. The Compact-SCR technology, on the other hand, has no means to limit sulfate emissions other than through lower catalytic function or lowering sulfur in diesel fuel. The degree to which the NOx emission control technologies increase the production of sulfate PM through oxidation of SO₂ to SO₃ varies somewhat from technology to technology, but it is expected to be similar in magnitude and environmental impact to that for the PM control technologies discussed previously in section III.A.7.a.ii, since both the NOx and the PM control catalysts rely on precious metals to achieve the required NO to NO₂ oxidation reaction.

At fuel sulfur levels below 15 ppm this sulfate PM concern is greatly diminished. Without this low sulfur fuel, the NOx control technologies are expected to create PM emissions well in excess of the PM standard regardless of the engine-out PM levels.

c. Contribution of Sulfur from Engine Lubricating Oils

Current engine lubricating oils have sulfur contents which can range from 2,500 ppm to as high as 8,000 ppm by weight. Since engine oil is consumed by heavy-duty diesel engines in normal operation, it is important that we account for the contribution of oil derived sulfur in our analysis of the need for low sulfur diesel fuel. One way to give a straightforward comparison of this effect is to express the sulfur consumed by the engine as an equivalent fuel sulfur level. This approach requires that we assume specific fuel and oil consumption rates for the engine. Assuming that a heavy-duty diesel engine consumes one quart of engine oil in 2,000 miles of operation, that engine oil sulfur levels range from 2,000 to 8,000 ppm, and that the engine consumes fuel at a rate of one gallon per six miles of operation, the range of equivalent fuel sulfur levels can be estimated. Using these assumptions, the estimated range is from two to seven ppm diesel fuel sulfur equivalence.¹¹⁹ If values at the upper end of this range accurately reflect the contribution of sulfur from engine oil to the exhaust this would be a concern as it would represent as much as half of the total sulfur in the exhaust under a 15 ppm diesel fuel sulfur cap (with an average sulfur level assumed to be approximately seven to 10 ppm). However, we believe that this simplified analysis, while valuable in demonstrating the need to investigate this issue further, overstates the likely sulfur contribution from engine oil by a significant amount. Current heavy-duty diesel engines operate with open crankcase ventilation systems which “consume” oil by carrying oil from the engine crankcase into the environment. This consumed oil is correctly included in the total oil consumption estimates, but should not be included in estimates of oil entering the exhaust system for this analysis, since as currently applied this oil is not introduced into the exhaust. Thus the assumption of one quart of oil in 2,000 miles of operation being consumed and thus entering the exhaust system overstates the oil

contribution by the fraction of oil that exits from today's open crankcase systems. In the future we expect diesel engine manufacturers to rely on closed crankcase filtration systems to filter this oil from the blow-by gases and return the oil to the engine's crankcase, thus lowering engine oil consumption.

As an alternate approach to estimate the amount of oil and thus oil borne sulfur present in the exhaust, projected emission rates for Phase 1 technology engines can be made. The Phase 1 HD emission standards set a 0.1 g/bhp-hr PM emission rate for all classes of heavy-duty diesel vehicles. If we assume that virtually all oil consumed by the engine is emitted as diesel PM and that this soluble organic fraction (SOF) makes up 30 percent of diesel PM we can estimate how much oil is consumed. This estimate is made assuming that the engine oil has a sulfur content of 5,000 ppm, that 30 percent of PM emissions are from engine oil, and that the engine brake specific fuel consumption rate is 0.300 lbm/bhp-hr. The equivalent fuel sulfur level from engine oil is then calculated as

$$\text{sulfur level [ppm]} = \frac{(5,000 \text{ [ppm]} \times 0.1 \text{ [g/bhp-hr]} \times 30 \text{ [\%]})}{(454 \text{ [g/lbm]} \times 0.300 \text{ [lbm/bhp-hr]})}$$

A higher fuel consumption rate decreases the relative amount of sulfur from engine oil in this estimate. Using this approach we have estimated that the equivalent fuel sulfur level from engine oil is approximately one ppm.

As a further attempt to better understand the amount of sulfur contributed from engine oil in the exhaust we have looked at the results from the DECSE test program. The DECSE program reports sulfate emissions from a heavy-duty diesel engine equipped with highly catalyzed CDPFs and operated on diesel fuel at several fuel sulfur levels. A commonly used motor oil with sulfur content of approximately 3,500 ppm was chosen for this testing. Since the PM emission control technologies used in this testing are very sensitive to sulfur (converting sulfur to sulfate PM emissions at a rate of approximately 40 percent) they should reveal sensitivities to sulfur from lube oil. By taking the sulfate emission results reported by DECSE at fuel sulfur levels of 3 and 30 ppm sulfur we can estimate the amount of sulfate emissions (and thus sulfur contribution) from the engine oil. The intercept (the predicted sulfate emissions at 0 ppm sulfur fuel) of a straight-line fit through the two test points should reveal the amount of sulfate produced from oil derived sulfur. Figure III.A-21 shows the results of this analysis.¹²⁰ The intercept value shown in the figure is slightly below zero indicating that in spite of the high sulfur conversion rate typical of these emission control devices the amount of lube oil derived sulfate emissions is unmeasurable. Although some amounts of sulfur from lubricating oils are almost certainly present in the exhaust, this analysis seems to indicate that it will not be a significant fraction of the total sulfur even for fuel sulfur levels as low as 15 ppm.

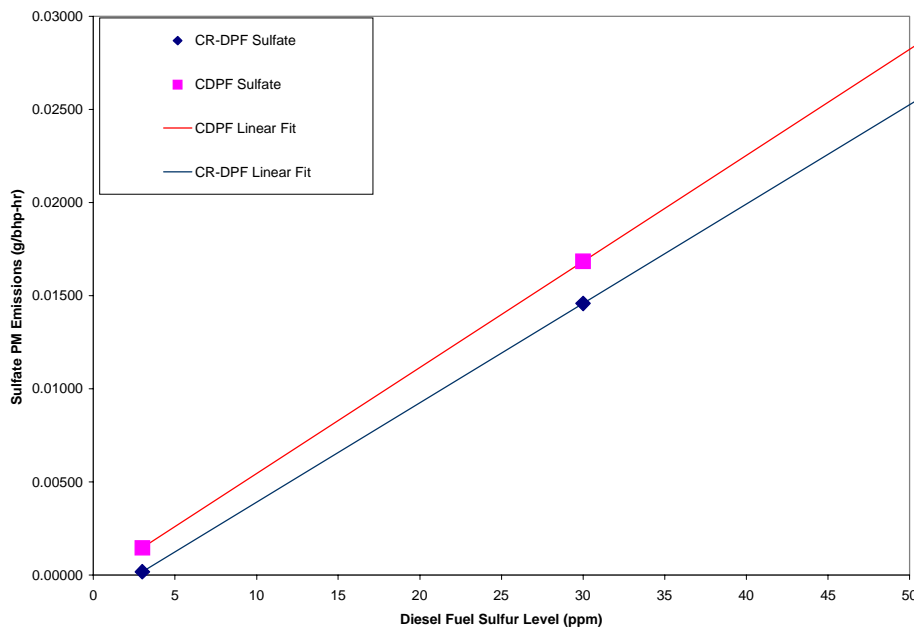


Figure III.A-21. Sulfate PM Emissions versus Diesel Fuel Sulfur Level with 3,500 ppm Sulfur Engine Oil

B. Feasibility of the 2008 Standards for Heavy-Duty Gasoline Vehicles & Engines

Gasoline emission control technology has evolved rapidly in recent years. Emission standards applicable to 1990 model year vehicles required roughly 90 percent reductions in exhaust HC and CO emissions and a 75 percent reduction in NO_x emissions compared to uncontrolled emissions. Since then, light-duty gasoline emission standards have undergone two major reductions, our Tier 1 and Tier 2 standards, and heavy-duty gasoline emission standards have undergone three changes toward ever lower levels. Despite that, some of today's heavy-duty vehicle emissions are well below levels necessary to meet the current federal heavy-duty gasoline standards, the Phase 1 heavy-duty gasoline standards to be implemented in the 2005 model year,¹²¹ and the California Low Emission Vehicle (LEV) standards for medium-duty vehicles.^u The continuing emissions reductions have been brought about by ongoing improvements in engine air-fuel management hardware and software plus improvements in exhaust system and catalyst designs.

^u The Phase 1 heavy-duty program is a reference to the 2004 heavy-duty final rule which set the 2004 model year HD diesel standards and the 2005 model year HD gasoline standards. (See 65 FR 59896, October 6, 2000) The 2007 final rule represents Phase 2 of this heavy-duty standard setting effort.

These improvements to gasoline emission controls have been made in response to the California LEV-II standards and the new federal Tier 2 standards.^{122 123} Some of this development work was contributed by EPA in a very short timeframe and with very limited resources in support of our Tier 2 rulemaking effort.¹²⁴ These improvements should transfer well to the heavy-duty gasoline segment of the fleet. Given the dramatic improvements in gasoline emission control technology in recent years, it is clear that there is no need to invent new technologies to meet emission levels below the 2005 heavy-duty gasoline standards. Instead, existing technologies can be applied to heavy-duty gasoline engines more effectively and more broadly; the focus being on the application and optimization of these existing technologies. With the migration of light-duty technology to heavy-duty vehicles and engines, we believe that considerable improvements to heavy-duty gasoline emissions can be realized, thus enabling the stringent 2008 standards.

The most significant improvement facilitating the low emission levels of today's gasoline vehicles has been to the traditional three-way catalyst, which now warms up and lights off very rapidly and is substantially more durable than in the past. Dramatic improvements have been realized also in fuel metering, which is now far more precise and accurate than previous systems. Improvements have been made also to base engine designs, which have resulted in lower engine-out emissions. Reduction of combustion chamber crevice volumes and oil consumption are examples of improvements to base engine designs. Equally important, if not more so, is that emission control calibrations continue to become more refined and sophisticated as calibrators become more skilled and computing power increases.

Fuel quality also plays an important role in improving vehicle emissions. In our Tier 2 rule for light-duty vehicles and trucks, we required that gasoline sulfur levels be reduced to a 30 ppm average with an 80 ppm cap. This sulfur level reduction is the primary enabler for the Tier 2 standards. Likewise for the 2008 heavy-duty gasoline standards. The Tier 2 gasoline sulfur reduction that enables the technology needed to meet the Tier 2 standards (0.07 g/mi NO_x, on average) will enable that same technology on heavy-duty gasoline vehicles, thus enabling the 2008 heavy-duty gasoline standards.

1. Gasoline Exhaust Emission Control Technology Descriptions

Table III.B-1 below lists specific types of exhaust emission controls that we project may be used on heavy-duty gasoline vehicles to meet the 2008 heavy-duty gasoline standards. We do not believe that all of these technologies would be needed to meet the 2008 standards on every vehicle. The choices manufacturers make and the combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of existing emission control systems, and individual manufacturer preferences. In some cases, such as the need for increases in catalyst volume and precious metal loading, we believe that most, if not all, vehicles will use the technology.

Table III.B-1. Exhaust Emission Control Hardware and Technologies That May be Used to Meet the 2008 Heavy-Duty Gasoline Standards

Fast Light-Off Exhaust Gas Oxygen Sensor	Secondary Air Injection Exhaust
Retarded Spark Timing at Start-Up	Heat Optimized Exhaust Pipe
More Precise Fuel Control	Leak-Free Exhaust System
32-bit Microprocessor	Close-Coupled Catalyst
Manifold with Low Thermal Capacity	Improved Catalyst Washcoats
Air-Assisted Fuel Injection	Increased Catalyst Volume and Precious Metal Loading
Engine Modifications	Full Electronic Exhaust Gas Recirculation

This section discusses in detail some of the technologies that may be used to meet the 2008 standards. The technology descriptions are divided into five categories:

- base engine improvements;
- improved fuel control;
- improved fuel atomization;
- improved exhaust and exhaust emission control systems; and
- improved engine calibrations.

a. Base Engine Improvements

There are several design techniques that can be used for reducing engine-out emissions, especially for HC and NO_x. The main causes of excessive engine-out emissions are unburned HCs and high combustion temperatures for NO_x. Methods for reducing engine-out HC emissions include the reduction of crevice volumes in the combustion chamber, reducing the combustion of lubricating oil in the combustion chamber and developing leak-free exhaust systems. Leak-free exhaust systems are considered to be base engine improvements because any modifications or changes made to the exhaust manifold can directly affect the design of the base engine. Base engine control strategies for reducing NO_x include the use of “fast burn”

combustion chamber designs, multiple valves with variable-valve timing, and exhaust gas recirculation.

i. Combustion Chamber Design

Unburned fuel can be trapped momentarily in crevice volumes (i.e., the space between the piston and cylinder wall) before being subsequently released. Since trapped and re-released fuel can increase engine-out HC, the reduction of crevice volumes is beneficial to emission performance. One way to reduce crevice volumes is to design pistons with reduced top “land heights.”^v The reduction of crevice volume is especially desirable for vehicles with larger displacement engines, since they typically produce greater levels of engine-out HC than smaller displacement engines.

Another cause of excess engine-out HC emissions is the combustion of lubricating oil that leaks into the combustion chamber, since heavier hydrocarbons in oil do not oxidize as readily as those in gasoline. Oil in the combustion chamber can also trap gaseous HC from the fuel and release it as an unburned HC. In addition, some components in lubricating oil can poison the catalyst and reduce its effectiveness. To reduce oil consumption, vehicle manufacturers are expected to tighten tolerances and improve the surface finishes of cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber.

As discussed above, engine-out NO_x emissions result from high combustion temperatures. Therefore, the main control strategies for reducing engine-out NO_x are designed to lower combustion temperature. The most promising techniques for reducing combustion temperatures, and thus engine-out NO_x emissions, are the combination of increasing the rate of combustion, reducing spark advance, and adding a diluent to the air-fuel mixture, typically via exhaust gas recirculation (EGR). The rate of combustion can be increased by using “fast burn” combustion chamber designs. A fast burn combustion rate provides improved thermal efficiency and a greater tolerance for dilution from EGR resulting in better fuel economy and lower NO_x emissions. There are numerous ways to design a fast burn combustion chamber. However, the most common approach is to induce turbulence into the combustion chamber which increases the surface area of the flame front and thereby increases the rate of combustion. Many engine designs induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as “swirl”). Further improvements can be realized by positioning the spark plug in the center of the combustion chamber. Locating the spark plug in the center of the combustion chamber promotes more thorough combustion and allows the ignition timing to be retarded, decreasing the dwell time of hot gases in the combustion chamber thereby reducing NO_x formation.

^v “Land height” is the distance between the top of the piston and the first piston ring.

ii. Improved EGR Design

One of the most effective means of reducing engine-out NO_x emissions is exhaust gas recirculation. By recirculating exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NO_x. As discussed above, the use of high swirl, high turbulence combustion chambers can allow the amount of EGR to be increased from current levels of 15 to 17 percent to levels possibly as high as 20 to 25 percent,^w resulting in a 15 to 20 percent reduction in engine-out NO_x emissions.

Many EGR systems in today's vehicles utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NO_x emissions for most vehicles in the past, more stringent NO_x standards may require more precise EGR control to improve upon NO_x emission control. Some manufacturers use a mechanical back-pressure system that measures EGR flow (via delta pressure across an orifice) rather than inferring flow from the EGR pintle position. This system uses electronic control of the vacuum actuation and has very precise control. Many manufacturers are now using electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can, in some cases, be more precisely controlled.

While most manufacturers agree that electronic EGR gives more precise control of EGR flow rate, not all manufacturers are using it. Numerous heavy-duty gasoline applications certified for the 1998 model year still use mechanical EGR systems, and in some cases, no EGR at all. Nonetheless, the use of EGR remains a very important tool in reducing engine-out NO_x emissions, whether mechanical or electronic.

iii. Multiple Valves and Variable-Valve Timing

Conventional engines have two valves per cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combustion products. The duration and lift (distance the valve head is pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for

^w Some manufacturers have stated that EGR impacts the ability to control net air-fuel ratios tightly due to dynamic changes in exhaust back pressure and temperature, and that the advantages of increasing EGR flow rates are lost partly in losses in air-fuel ratio control even with electronic control of EGR. Higher EGR flow rates can be tolerated by modern engines with more advanced combustion chambers, but EGR cooling may be necessary to achieve higher EGR flow rates within acceptable detonation limits without significant loss of air-fuel control.

intake and exhaust also increases. By doubling the number of intake and exhaust valves, pumping losses are reduced, improving the volumetric efficiency and useful power output.

In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency thereby lowering engine-out HC emissions.

Even greater improvements to combustion efficiency can be realized by using valve timing and lift control to take advantage of the 4-valve configuration. Conventional engines utilize fixed-valve timing and lift across all engine speeds. Typically the valve timing is set at a level that is a compromise between low speed torque and high engine speed horsepower. At light engine loads it would be desirable to close the intake valve earlier to reduce pumping losses. Variable valve timing can enhance both low speed torque and high speed horsepower with no necessary compromise between the two. Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions. Variable valve technology by itself may have somewhat limited effect on reducing emissions. Several vehicle manufacturers estimated emission reductions of 3 percent-10 percent for both NMHC and NO_x, but reductions could be increased when variable valve timing is combined with optimized spark plug location and additional EGR.

Multi-valve engines already exist in numerous federal and California certified vehicles and are projected by ARB to become even more common. ARB also projects that, in order to meet LEV-II LEV and ULEV standards, more vehicles will have to make improvements to the induction system, including the use of variable valve timing.

iv. Leak-Free Exhaust Systems

Leaks in the exhaust system can result in increased emissions, but not necessarily from emissions escaping from the exhaust leak to the atmosphere. With an exhaust system leak, ambient air is typically sucked into the exhaust system by the pressure difference created by the flowing exhaust gases inside the exhaust pipe. The air that is sucked into the exhaust system is unmeasured and, therefore, unaccounted for in the fuel system's closed-loop feedback control. The excess air in the exhaust causes the computer to increase fuel to the engine, resulting in erratic and/or overly rich fuel control. This results in increased emission levels and potentially poor driveability. In addition, an air leak can cause an oxidation environment to exist in a three-

way catalyst at low speeds that would hamper reduction of NO_x and lead to increased NO_x emissions.

Some vehicles currently use leak-free exhaust systems today. These systems consist of an improved exhaust manifold/exhaust pipe interface plus a corrosion-free flexible coupling inserted between the exhaust manifold flange and the catalyst to reduce stress and the tendency for leakage to occur at the joint. In addition, improvements to the welding process for catalytic converter canning could ensure less air leakage into the converter and further reduce emissions.

b. Improvements in Air-Fuel Ratio Control

Modern three-way catalysts require the air-fuel ratio (A/F) to be as close to stoichiometry (the amount of air and fuel just sufficient for nearly complete combustion) as possible. This is because three-way catalysts simultaneously oxidize HC and CO, and reduce NO_x. Since HC and CO are oxidized during A/F operation slightly lean of stoichiometry, while NO_x is reduced during operation slightly rich of stoichiometry, there exists a very small A/F window of operation around stoichiometry where catalyst conversion efficiency is maximized for all three pollutants (i.e., less than one percent deviation in A/F or roughly ± 0.15). Contemporary vehicles have been able to maintain stoichiometry, or very close to it, by using closed-loop feedback fuel control systems. At the heart of these systems has been a single heated exhaust gas oxygen (HEGO) sensor. The HEGO sensor continuously switches between rich and lean readings. By maintaining an equal number of rich readings with lean readings over a given period, and by limiting the degree to which the exhaust is rich or lean at any point in time, the fuel control system is able to maintain stoichiometry. While this fuel control system is capable of maintaining the A/F with the required accuracy under steady-state operating conditions, the system accuracy is challenged during transient operation where rapidly changing throttle conditions occur. Also, as the sensor ages, its accuracy decreases.

i. Dual Oxygen Sensors

Many vehicle manufacturers have placed a second HEGO sensor(s) downstream of one or more catalysts in the exhaust system as a method for monitoring the catalyst effectiveness of the federally and California mandated on-board diagnostic (OBD II) system. In addition to monitoring the effectiveness of the catalyst, the downstream sensors can also be used to monitor the primary control sensor and adjust for deterioration, thereby maintaining precise A/F control at higher mileages. Should the front primary HEGO sensor, which operates in a higher temperature environment, begin to exhibit slow response or drift from its calibration point, the secondary downstream sensor can be relied upon for modifying the fuel system controls to compensate for the aging effects. By placing the second sensor further downstream from the hot engine exhaust, where it is also less susceptible to poisoning, the rear sensor is less susceptible to aging over the life of the vehicle. Because of this placement and the decreased susceptibility to aging, we

expect the downstream sensor to survive the full life of the vehicle without replacement. As a result, the use of a dual oxygen sensor fuel control system can ensure more robust and precise fuel control, resulting in lower emissions.

By 2008, most vehicle manufacturers are expected to use a dual oxygen sensor system for monitoring the catalyst as part of the OBD system required by the Phase 1 heavy-duty rule. As discussed above, most manufacturers also will use the secondary HEGO sensor for fuel trim (i.e., minor adjustments) of the fuel control system. We anticipate that all manufacturers will use this secondary sensor for fuel trim.

ii. Universal Oxygen Sensors

The universal exhaust gas oxygen (UEGO) sensor, also called a "linear oxygen sensor", could replace conventional HEGO sensors. Conventional HEGO sensors only determine if an engine's A/F is richer or leaner than stoichiometric, providing no indication of the exact level of the A/F. In contrast, UEGO's are capable of recognizing both the direction and magnitude of A/F transients since the voltage output of the UEGO is "proportional" with changing A/F (i.e., each voltage value corresponds to a certain A/F). Therefore, proportional A/F control is possible with the use of UEGO sensors, facilitating faster response of the fuel feedback control system and tighter control of A/F.

Although some gasoline applications currently use UEGO sensors, discussions with various manufacturers suggest mixed opinions as to the future applicability of UEGO sensors. Because of their high cost, manufacturers claim that it may be cheaper to improve HEGO technology rather than utilize UEGO sensors. An example of this is the use of a "planar" design for HEGO sensors. Planar HEGO sensors (also known as "fast light-off" HEGO sensors) have a thimble design that is considerably lighter than conventional designs. The main benefits are shorter heat-up time and faster sensor response.

iii. Individual Cylinder A/F Control

Another method for tightening fuel control is to control the A/F in each individual cylinder. Current fuel control systems control the A/F for the entire engine or a bank of cylinders. By controlling A/F for the entire engine or a bank of cylinders, any necessary adjustments made to fuel delivery for the engine are applied to all cylinders simultaneously, regardless of whether all cylinders need the adjustment. For example, there is usually some deviation in A/F between cylinders. If a particular cylinder is rich, but the "bulk" A/F indication for the engine is lean, the fuel control system will simultaneously increase the amount of fuel delivered to all of the cylinders, including the rich cylinder. Thus, the rich cylinder becomes even richer having a potentially negative effect on the net A/F.

Individual cylinder A/F control helps diminish variation among individual cylinders. This is accomplished by modeling the behavior of the exhaust gases in the exhaust manifold and using sophisticated software algorithms to predict individual cylinder A/F. Individual cylinder A/F control requires use of an UEGO sensor in lieu of the traditional HEGO sensor, and requires a more powerful engine control computer.

iv. Adaptive Fuel Control Systems

The fuel control systems of virtually all current vehicles incorporate a feature known as “adaptive memory” or “adaptive block learn.” Adaptive fuel control systems automatically adjust the amount of fuel delivered to compensate for component tolerances, component wear, varying environmental conditions, varying fuel compositions, etc., to more closely maintain proper fuel control under various operating conditions.

For most fuel control systems in use today, the adaption process affects only steady-state operation conditions (i.e., constant or slowly changing throttle conditions). Because transient operating conditions have always provided a challenge to maintaining precise fuel control, the use of adaptive fuel control for transient operation would be extremely valuable. Accurate fuel control during transient driving conditions has traditionally been difficult because of inaccuracies in predicting the air and fuel flow under rapidly changing throttle conditions. Air and fuel dynamics within the intake manifold (fuel evaporation and air flow behavior), and the time delay between measurement of air flow and the injection of the calculated fuel mass, result in temporarily lean A/F during transient operation. Variation in fuel properties, particularly distillation characteristics, also increases the difficulty in predicting A/F during transients. These can all lead to poor driveability and an increase in NO_x emissions.

v. Electronic Throttle Control Systems

As mentioned above, the time delay between the air mass measurement and the calculated fuel delivery presents one of the primary difficulties in maintaining accurate fuel control and good driveability during transient driving conditions. With the conventional mechanical throttle system (a metal linkage connected from the accelerator pedal to the throttle blade in the throttle body), quick throttle openings can result in a lean A/F spike in the combustion chamber. Although algorithms can be developed to model air and fuel flow dynamics to compensate for these time delay effects, the use of an electronic throttle control system, known as “drive-by-wire” or “throttle-by-wire,” may better synchronize the air and fuel flow to achieve proper fueling during transients (e.g., the driver moves the throttle, but the fuel delivery is momentarily delayed to match the inertial lag of the increased airflow).

While this technology is currently used on several gasoline applications, it is considered expensive and those vehicles equipped with the feature are expensive, higher end vehicles.

Because of its high cost, it is not anticipated that drive-by-wire technology will become commonplace in the near future.

c. Improvements in Fuel Atomization

In addition to maintaining a stoichiometric A/F ratio, it is also important that a homogeneous air-fuel mixture be delivered at the proper time and that the mixture is finely atomized to provide the best combustion characteristics and lowest emissions. Poorly prepared air-fuel mixtures, especially after a cold start and during the warm-up phase of the engine, result in significantly higher emissions of unburned HC since combustion of the mixture is less complete. By providing better fuel atomization, more efficient combustion can be attained, which should aid in improving fuel economy and reducing emissions. Sequential multi-point fuel injection and air-assisted fuel injectors are examples of the most promising technologies available for improving fuel atomization.

i. Sequential Multi-Point

Typically, conventional multi-point fuel injection systems inject fuel into the intake manifold by injector pairs. This means that rather than injecting fuel into each individual cylinder, a pair of injectors (or even a whole bank of injectors) fires simultaneously, sending fuel into several cylinders. Since only one of the cylinders is actually ready for fuel at the moment of injection, the other cylinder(s) gets too much or too little fuel. With this less than optimum fuel injection timing, fuel puddling and intake manifold wall wetting can occur, both of which can hinder complete combustion. Sequential injection, on the other hand, delivers a more precise amount of fuel that is required by each cylinder to each cylinder at the appropriate time. Because of the emission reductions and other performance benefits “timed” fuel injection offers, sequential fuel injection systems are very common on today’s vehicles and are expected to be incorporated in all vehicles soon.

ii. Air-Assisted Fuel Injectors

Another method used to further homogenize the air-fuel mixture is to use air-assisted fuel injection. By injecting high pressure air into the fuel injector, and subsequently, the fuel spray, greater atomization of the fuel droplets can occur. Since achieving good fuel atomization is difficult when the air flow into the engine is low, air-assisted fuel injection can be particularly beneficial in reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold.

d. Improvements to Exhaust and Exhaust Emission Control Systems

Over the last five years or so, there have been tremendous advancements in exhaust emission control systems. Catalyst manufacturers have been progressively moving to palladium as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advancements made to catalyst technology. There has also been much development in HC and NO_x adsorber technology. The advancements to exhaust emission control systems are probably the single most important area of emission control development.

i. Catalysts

As previously mentioned, significant changes in catalyst formulation, size and design have been made in recent years and additional advances in these areas are still possible. Palladium (Pd) is likely to continue as the precious metal of choice for close-coupled applications and may start to see more use in underfloor applications. Some manufacturers, for example, have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. Palladium catalysts, however, are less resistant to poisoning by oil-and fuel-based additives than conventional platinum/rhodium (Pt/Rh) catalysts. Based on current certification trends and information from vehicle manufacturers and catalyst suppliers, it is expected that Pd-only and Pd/Rh catalysts will be used in the close-coupled locations while conventional Pd/Rh, Pt/Rh or tri-metal (Pd/Pt/Rh) catalysts will continue to be used in underfloor applications. As palladium technology continues to improve, it may be possible for a single close-coupled catalyst to replace both catalysts. In fact, at least one vehicle manufacturer currently uses a single Pd-only catalyst for one of their gasoline applications. According to MECA, new Pd-based catalysts are now capable of withstanding exposure to temperatures as high as 1100°C and, as a result, can be moved very close to the exhaust manifold to enhance catalyst light-off performance.

In addition to an increased reliance on Pd, catalyst manufacturers have developed “multi-layered” washcoat technologies. Automotive catalysts consist of a cylindrical or oval shaped substrate, typically made of ceramic or metal. The substrate is made up of hundreds of very small, but long cells configured in a shape similar to a honey-comb. The substrate is coated with a substance containing precious metals, rare earth metals, and base-metal oxides, that is known as the catalyst washcoat. Typical washcoat formulations consist of precious metals which either oxidize or reduce pollutants, base-metal oxides, such as alumina, that provide the surface area support to which the precious metals adhere, and base components (rare earth metals) such as lanthanum, ceria, and zirconia, that act as promoters and stabilizers while also encouraging storage and reduction of oxygen.

Conventional catalysts have a single layer of washcoat and precious metals applied to the catalyst substrate. More advanced catalysts use multi-layered washcoats with two or more layers of different combinations of washcoat and precious metals. The washcoat can be applied to the substrate such that one layer can be applied on top of another. The use of multi-layered washcoat technology allows precious metals that have adverse reactions together to be separated such that catalyst durability and emission reduction performance are significantly enhanced. For example, Pd and Rh can have adverse reactions when combined together in a single washcoat formulation. A multi-layer washcoat architecture that uses Pd and Rh could have the Pd on the bottom layer and the Rh on the top layer. Rhodium is primarily used for reducing NO_x emissions. Generally, and preferably, NO_x emissions are reduced in the top washcoat layer while CO and HC are still present. Then, the CO and HC can be oxidized in the bottom washcoat layer. Figure III.B-1 illustrates the impact coating architecture (multi-layered washcoat technology) can have on emission performance.^x

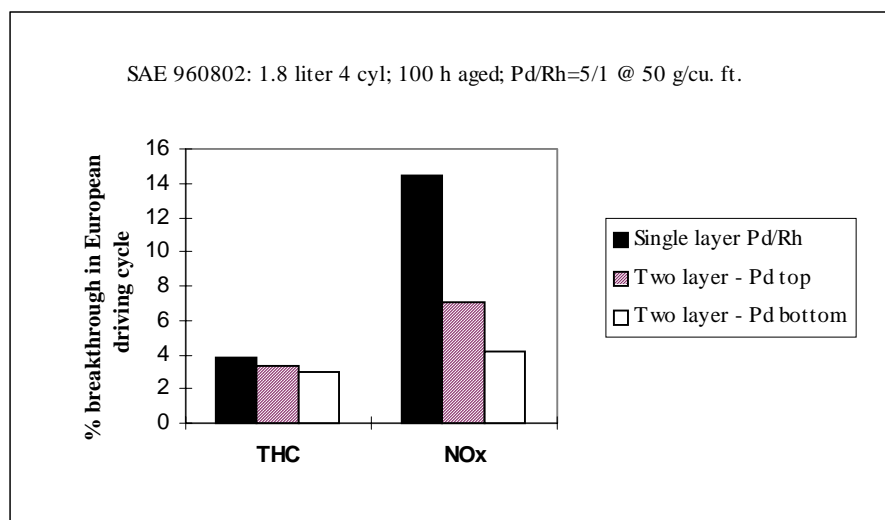


Figure III.B-1. Impact of Coating Architecture on HC and NO_x Emissions

Manufacturers also have been developing catalysts with thinner walled substrates that allow for a higher substrate cell density, and low thermal mass catalysts for close-coupled applications. These developments improve mass transfer at high engine loads, increase catalyst surface area, and speed up light-off time during cold starts. The greater the number of cells there are, the more surface area that exists to which washcoat components and precious metals can

^x Figure III.B-1 shows “% breakthrough in European driving cycle” on the y-axis; this can be defined as the percentage of emissions that pass through the catalyst without being converted to H₂O, CO₂, and N₂ during the European test cycle.

adhere. This results in more precious metal sites available for oxidizing and reducing pollutants. Cell densities of 600 cells per square inch (cpsi) have already been commercialized, and research on 900 and 1200 cpsi catalysts has been progressing. Typical cell densities for today's conventional catalysts are 400 cpsi.

We also have projected that, in order to meet the 2008 heavy-duty gasoline emission standards, catalyst volumes would have to increase. Current heavy-duty gasoline applications have catalyst volumes slightly lower than the corresponding engine displacement. We believe that most heavy-duty gasoline vehicles would likely need to increase catalyst volumes on the order of ten percent. As mentioned above, higher cell density substrates effectively provide more surface area for pollutant conversion. Therefore, catalyst volumes may not need to be increased as significantly if higher cell density substrates are used.

We also have projected that some level of increased precious metal loading (i.e., catalyst loading) would be necessary to meet the 2008 heavy-duty gasoline standards. Typical catalyst loadings for current heavy-duty gasoline applications are four grams/liter (g/L) of catalyst volume. We believe that, based on input from catalyst suppliers and vehicle manufacturers, catalysts meeting the 2008 standards would need loadings more on the order of five g/L. However, catalyst suppliers have also indicated to us that they and vehicle manufacturers are constantly working on ways to reduce the amount of precious metal loading (a process they refer to as "thrifting"). Thrifting is achieved in several ways. One of the most common is matching the catalyst to the attributes of the vehicle. By working in unison, vehicle manufacturers and catalyst suppliers are able to thrift or reduce the amount of precious metal used in a given application by attempting to optimize the vehicle fuel control strategy, exhaust mass flow rate, and exhaust temperature with various catalyst parameters, such as catalyst location, substrate design, cell density, oxygen storage capability, and precious metal and base metal dispersion, to name a few. Other methods of thrifting are the constant improvements being made to washcoat architecture - that is, constant improvement to the materials used in the washcoat formulation so that the precious metals and other components better adhere to the substrate surface. Finally, improvements to washcoat application processes also can improve significantly the catalyst performance while still allowing for thrifting of precious metals. Improvements to processes consist of advancements to the process used to coat the substrate with washcoat materials - allowing precious metals, base metals, and ceria to be better dispersed. Better precious metal dispersion means that, rather than having relatively large "clumps" of precious metals unevenly dispersed throughout the catalyst surface, many smaller precious metal sites are dispersed uniformly throughout the catalyst surface. This type of dispersion increases the chance for pollutants to come into contact with the precious metal and thus react into a harmless emission. Therefore, as thrifting continues, precious metal loading may actually decrease rather than increase, although this very likely outcome has not been incorporated into our cost estimates presented in Chapter V of this RIA.

The largest source of HC emissions continues to be cold start operation where the combination of rich A/F operation and the ineffectiveness of a still relatively cool catalyst results in excess HC emissions. One of the most effective strategies for controlling cold start HC emissions is to reduce the time it takes to increase the operating temperature of the catalyst immediately following engine start-up. The effectiveness, or efficiency, of the catalyst increases as the catalyst temperature increases. One common strategy is to move the catalyst closer to the exhaust manifold where the exhaust temperature is greater (e.g., a close-coupled catalyst). In addition to locating the catalyst closer to the engine, retarding the spark timing and increasing idle speed are other possible approaches. Retarding spark timing causes combustion to occur later in the power stroke. This results in more heat escaping into the exhaust manifold during the exhaust stroke while having a negligible impact on fuel economy.¹²⁵ Increased idle speed leads to a greater amount of combustion per unit time, providing a greater quantity of heat for heating the exhaust manifold, headpipe, and catalyst.

ii. Secondary Air Injection

Secondary injection of air into exhaust ports after cold start (e.g., the first 40-60 seconds) when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. By means of an electrical pump, secondary air is injected into the exhaust system, preferably in close proximity of the exhaust valve. Together with the oxygen of the secondary air and the hot exhaust components of HC and CO, oxidation ahead of the catalyst can bring about an efficient increase in the exhaust temperature which helps the catalyst to heat up more quickly. The exothermic reaction that occurs is dependent on several parameters (secondary air mass, location of secondary air injection, engine A/F ratio, engine air mass, ignition timing, manifold and headpipe construction, etc.), and ensuring reproducibility demands a detailed individual application for each vehicle or engine design.

iii. Heat Managed Exhaust Systems

Insulating the exhaust system is another method of furnishing heat to the catalyst to decrease light-off time. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve heat generated in the engine to aid the catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off.

e. Improvements in Engine Calibration Techniques

Of all the technologies discussed above, one of the most important emission control strategies is not hardware-related. Rather, it is software related and, more specifically, involves the algorithms and calibrations contained within the software that are used in the power-train

control module (PCM) which control how the various engine and emission control components and systems operate. Advancements in software along with refinements to existing algorithms and calibrations can have a major impact in reducing emissions.

As computer technology and software continues to advance, so does the ability of the automotive engineer to use these advancements in ways to better optimize the emission control systems. For example, as processors become faster, it is possible to perform calculations more quickly, thus allowing for faster response times for controlling engine parameters, such as fuel rate and spark timing. As engine and powertrain control modules become more powerful with greater memory capability, algorithms can become more sophisticated. Manufacturers have found that as computer processors, engine control sensors and actuators, and computer software become more advanced, and, in conjunction with their growing experience with developing calibrations, as time passes, their calibration skills will continue to become more refined and robust, resulting in even lower emissions.

Manufacturers have suggested to us that perhaps the single most effective method for controlling NO_x emissions will be tighter A/F control which could be accomplished with advancements in calibration techniques without necessarily having to use advanced technologies, such as UEGO sensors. Manufacturers have found ways to improve calibration strategies such that meeting federal cold CO requirements and complying with stringent light-duty LEV and NLEV standards has not required the use of advanced hardware, such as electrically heated catalysts or HC adsorbers as some had originally predicted they would need.

Since emission control calibrations are typically confidential, it is difficult to predict what advancements will occur in the future, but it is clear that improved calibration techniques and strategies are a very important and viable method for further reducing emissions.

2. The 2008 Heavy-Duty Gasoline Exhaust Emission Standards

The 2008 heavy-duty gasoline complete vehicle standards are equivalent to the California LEV-II program LEV standards for vehicles in the same weight ranges, with the exception of the PM standards. The 2008 NO_x level for 8,500 to 10,000 pound vehicles is 0.2 g/mi and the NO_x level for 10,000 to 14,000 pound vehicles is 0.4 g/mile. The NMHC standards are 0.195 and 0.23 g/mile for the 8,500 to 10,000 pound and 10,000 to 14,000 pound vehicles, respectively. The California LEV-II LEV standards for PM emissions are 0.12 g/mi, while the new federal heavy-duty vehicle PM standard will be 0.02 g/mi. The California PM standards were originally set with consideration given to diesel vehicles not equipped with emission control devices, hence the much higher level than finalized for federal heavy-duty vehicles.

The 2008 heavy-duty gasoline incomplete vehicle standards, for which California has no standards as all gasoline vehicles are required by California to certify on the chassis

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dynamometer, are 0.20 g/bhp-hr NO_x, 0.14 g/bhp-hr NMHC, and 0.01 g/bhp-hr PM. Table III.B-2 shows the new 2008 heavy-duty gasoline exhaust emission standards along with the California emission standards for the equivalent vehicles. Also shown in Table III.B-2 are some of the federal Tier 2 bin levels for the purpose of comparison with the standards for light-duty trucks and medium-duty passenger vehicles (MDPVs).^y

Table III.B-2. Emission Standards for Select Federal and California Gasoline Vehicles & Engines

<i>Program</i>	<i>Weight Range or Tier 2 Bin</i>	<i>Useful Life (mi)</i>	<i>NO_x</i>	<i>NMHC^A</i>	<i>HCHO</i>	<i>PM</i>
Phase 2 Heavy-Duty Gasoline <u>Phase-in:</u> 2008: 50% 2009: 100%	Vehicles 8,500-10,000 lbs (g/mi)	120,000	0.2	0.195	0.032	0.02
	Vehicles 10,000-14,000 lbs (g/mi)	120,000	0.4	0.230	0.040	0.02
	Engines > 8,500 lbs (g/bhp-hr)	110,000	0.20	0.14	N/A	0.01
Cal LEV-II MDV (LEV Only) <u>Phase-in:</u> 2004-2006 2007: 40% ^B	8,500-10,000 lbs (g/mi)	120,000	0.2	0.195	0.032	0.12
	10,000-14,000 lbs (g/mi)	120,000	0.4	0.230	0.040	0.12
Tier 2 Light-Duty <u>Phase-in:</u> 2004-2009 MDPV Bin available only thru 2008	MDPV Interim Bin (g/mi)	120,000	0.9	0.28	0.032	0.12
	Final High Bin (g/mi)	120,000	0.20	0.125	0.018	0.02
	Average Bin (g/mi)	120,000	0.07	0.09	0.018	0.01

^A Non-methane hydrocarbon (NMHC) or, for LEV-II and Tier 2, non-methane organic gas (NMOG).

^B In 2007, the remaining 60% of California MDVs must be certified to the more stringent ULEV levels.

^y Medium-duty passenger vehicles are defined as any complete vehicle between 8,500 and 10,000 pounds GVWR designed primarily for the transportation of persons. The definition specifically excludes any vehicle that (1) has a capacity of more than 12 persons total or, (2) is designed to accommodate more than 9 persons in seating rearward of the driver's seat or, (3) has a cargo box (e.g., pick-up box or bed) of six feet or more in interior length. (See the Tier 2 final rulemaking, 65 FR 6698, February 10, 2000.)

The standards shown in Table III.B-2 for the 2008 heavy-duty gasoline vehicles and engines are phased-in on 50 percent of vehicles and engines in the 2008 model year, and 100 percent in the 2009 model year. Under the California LEV-II program, by the 2007 model year manufacturers are required to build at least 40 percent of their MDVs to the LEV category standards shown in Table III.B-2, and 60 percent of their MDVs to the tighter ULEV category standards. The LEV-II ULEV category standards for MDVs are, for NO_x and NMOG respectively, 0.2 and 0.143 g/mi for 8,500 to 10,000 pounds, and 0.4 and 0.167 g/mi for 10,000 to 14,000 pounds.¹²⁶

Under the federal Tier 2 program, the MDPVs are the vehicles most similar to the heavy-duty gasoline vehicles required to meet the 2008 HD gasoline standards. During the 2008 model year, half of the MDPVs can be certified in the MDPV interim bin shown in Table III.B-2, while the other half must be certified within the final Tier 2 bin structure and included in the manufacturer's corporate average NO_x standard of 0.07 g/mi NO_x.¹²⁷ The highest bin in the final Tier 2 structure is the final high bin shown in Table III.B-2. Then, in the 2009 model year, the MDPV interim bin is no longer available and all MDPVs must be certified in the final Tier 2 bin structure and included in the 0.07 g/mi NO_x corporate average standard.

Therefore, the phase-in of the 2008 heavy-duty gasoline standards provides consistency with the Tier 2 program because the standards affecting similarly sized vehicles are phased-in on the same schedule. Further, those heavy-duty vehicles being phased-out (i.e., those 50 percent not meeting the new standard), would be certified to the Phase 1 heavy-duty gasoline standards which are equal to the MDPV interim bin for 8,500 to 10,000 pounds.¹²⁸ Again, the standard structure and implementation timing are consistent.

The engine standards shown in Table III.B-2 are equal to the engine standards set for diesel engines over 8,500 pound incomplete vehicles. For diesel engines, those standards are phased-in on a 50/50/50/100 percent schedule beginning in the 2007 model year. For gasoline engines, the phase-in schedule is consistent with the gasoline vehicle phase-in schedule of 50/100 percent beginning in the 2008 model year. This provides consistency and cost efficiency because the engines certified to the engine standards are the same engines being certified to the vehicle standards.

3. Current Exhaust Emission Certification Levels for Heavy-Duty Gasoline Vehicles & Engines

Tables III.B-3 and III.B-4 provide certification results from the 2000 model year for heavy-duty gasoline vehicles and engines, respectively. The vehicle data is California medium-duty vehicle (MDV) certification data and the engine data is EPA certification data. The tables provide an indication of the emission levels that are being achieved through the application of current emission control technologies.

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Table III.B-3 clearly shows that several vehicles have at least one emission constituent at or below the Phase 2 standards, and six vehicles have both NO_x and NMHC levels at or below the future standards. We recognize that not all of these levels necessarily comply with the Phase 2 standards because they provide little or no compliance margin. Nonetheless such low levels eight years prior to implementation suggest that the future standards are clearly within reach. Table III.B-4 shows that current engines are being designed to be near the Phase 2 standards for 2008 despite being certified to the much higher current standards of 4.0 g/bhp-hr NO_x and 0.9 g/bhp-hr NMHC. Based on industry input, we believe that manufacturers will continue the process of replacing their old engines with more advanced engines over the next several years. As new and more advanced engines are introduced, we anticipate that they will be capable of achieving the 2008 standards.

Table III.B-3. 2000 Model Year Vehicle Certification Data (gram/mile)^A

<i>Mfr</i>	<i>Same Eng Fam.</i>	<i>Model^B</i>	<i>Engine Size (liters)</i>	<i>GVWR (lbs.)</i>	<i>NO_x (g/mi)</i>	<i>HC^C (g/mi)</i>	<i>Stds</i>	<i>Sales Area^D</i>
Daimler Chrysler	Y	Ram 3500 Cab Chassis 4WD	5.9	11000	0.48	0.16	Tier1	CA
	Y	Ram 2500 P/U 4WD	5.9	8800	0.4	0.097	LEV	CA
					0.2	0.084		
	Y	Ram 2500 P/U 2WD	8.0	8800	0.41	0.2	Tier1	CA
		Ram 3500 P/U 4WD	8.0	10500	0.34	0.19		
	Y	Ram 3500 P/U 2WD	8.0	11000	0.56	0.22	Tier1	CA
					0.66	0.26		
					0.72	0.24		
	Y	B3500 Van 2WD	5.2	8700	0.29	0.14	Tier1	FA
		Ram 2500 Cab Chassis 4WD	5.9	8800	0.4	0.15		
Ford	Y	Excursion 4WD	5.4	8900	0.38	0.1675	LEV	CA
	Y	E350 2WD	5.3	9300	0.34	0.147	LEV	CA
					0.34	0.147	LEV	CF
	Y		6.8	9300	0.35	0.1615	LEV	CA
	Y	F350 4WD	6.8	11000	0.34	0.1421	LEV	CA
	Y	E250 Strip Chassis 2WD	4.2	8600	0.19	0.1003	LEV	CA
					0.19	0.1003	LEV	CF
	Y		4.2	8600	0.22	0.12	Tier1	FA
E250 Econoline 2WD		0.21			0.11			
General Motors	Y	K3500 P/U 4WD	5.7	10000	0.66	0.24	Tier1	CA
	Y		7.4		0.6	0.18	Tier1	CA
	Y	K2500 Silverado 4WD	6.0	8600	0.61	0.13	Tier1	CA
		K2500 Suburban 4WD	6.0	8600	0.67	0.17	Tier1	CA

^A Shaded entries are those at or below the Phase 2 emission standards.

^B Some of these models may be Tier 2 medium-duty passenger vehicles.

Table III.B-4. 2000 Model Year Engine Certification Data (g/bhp-hr)^A

<i>Mfr</i>	<i>Same Engine Family</i>	<i>Engine Size (liters)</i>	<i>Service Class</i>	<i>NOx (g/bhp-hr)</i>	<i>HC (g/bhp-hr)</i>	<i>NMHC (g/bhp-hr)</i>
DaimlerChrysler	Y	5.9	<14k	1.291	0.18	
	Y	8.0	<14k	1.14	0.13	
Ford	Y	5.4	CFE/ULEV	0.66	0.10	
	Y		<14k	0.66	0.10	
	Y	6.8	CFE/ULEV	0.48	0.13	
	Y		all	0.48	0.13	
	Y		<14k	0.48	0.12	
General Motors	Y	4.3	Fed <14k	0.9	0.2	
	Y	5.7	Fed CFE/LEV	2.7	0.3	0.2
	Y		50 State <14k	2.0	0.2	n/a
	Y	6.0	Fed CFE/LEV	1.7	0.3	0.2
	Y		50 State <14k	0.52	0.2	n/a
	Y	7.4	Fed CFE/LEV	1.7	0.6	0.5
	Y		50 State <14k	3.7	0.6	
	Y		50 State >14k	0.8	0.5	
	Y			3.7	0.6	

^A Shaded entries are those at or below the Phase 2 emission standards.

4. Technological Feasibility of the 2008 Heavy-Duty Gasoline Exhaust Emission Standards

We believe that the most promising overall emission control strategy for heavy-duty gasoline engines is the combination of improved three-way catalysts and improved electronic control of engine air-fuel ratio. Control of the air-fuel ratio is important because the three-way catalyst is only effective if the air-fuel ratio is at a narrow band near stoichiometry. For example, for an 80 percent conversion efficiency of HC, CO, and NOx with a typical three-way catalyst, the air-fuel ratio must be maintained within a fraction of one percent of stoichiometry. During transient operation, this minimal variation cannot be maintained with open-loop control. For

closed-loop control, the air-fuel ratio in the exhaust is measured by an oxygen sensor and used in a feedback loop. The throttle position, fuel injection, and spark timing can then be adjusted for given operating conditions to result in the proper air-fuel ratio in the exhaust. Most, if not all, engines have been equipped with closed loop controls. Some engines have been equipped with catalysts that are achieving catalyst efficiencies in excess of 95 percent. This is one key reason engine and vehicle certification levels are very low. In addition, electronic control can be used to adjust the air-fuel ratio and spark timing to adapt to lower engine temperatures, thereby controlling HC emissions during cold start operation.

All HD gasoline engines are equipped with three-way catalysts. Engines may be equipped with a variety of different catalyst sizes and configurations. Manufacturers choose catalysts to fit their needs for particular vehicles. Typically, current federal vehicle catalyst systems contain either a single converter, or two converters in series or in parallel.^z A converter is constructed of a substrate, a washcoat, and a catalytic material (e.g., precious metals). The substrate may be metallic or ceramic with a flow-through design similar to a honeycomb. Improvements in substrate and washcoat materials and technology have improved catalyst performance significantly in recent years. A high surface area washcoat is used to provide a suitable surface for the catalytic material. Under high temperatures, the catalytic material will increase the rate of chemical reaction of the exhaust gas constituents. Current catalyst systems on HD vehicles tend to have fairly low precious metal loading and total catalyst volumes typically 80 to 90 percent of engine volumes. Current precious metal loadings tend to be in the range of one to four g/L, and we expect most precious metal loadings to be up to four g/L for the purpose of meeting the 2005 standards.

Significant changes in catalyst formulation have been made in recent years and additional advances in these areas are still possible. Platinum, palladium and rhodium (Pt, Pd, and Rh) are the precious metals typically used in catalysts.^{aa} Historically, platinum has been widely used. Today, palladium is being used much more widely due to its ability to withstand very high exhaust temperatures. In fact, some HD vehicles currently are equipped with palladium-only catalysts. Other catalysts contain all three metals or contain no platinum but both palladium and rhodium. Some manufacturers have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. The underlying driver of which metals are used, and in what proportion, is the price of those metals. As platinum prices rise, more palladium is used; as palladium prices rise, more platinum is used. The same can be said of rhodium.

^z In contrast to some California LEV program medium-duty vehicles which have close-coupled catalysts.

^{aa} Platinum, palladium, and rhodium are platinum-group metals, or PGM, which also includes iridium, osmium, and ruthenium.

Chapter III: Emissions Standards Feasibility

We project that the 2008 heavy-duty gasoline standards will require the application of advanced engine and catalyst systems similar to those projected for their light-duty counterparts to meet the Tier 2 standards. The technologies and emission control strategies that will be used for medium-duty passenger vehicles (MDPVs), which have a GVWR greater than 8,500 pounds, should also apply directly to heavy-duty gasoline vehicles. Historically, manufacturers have introduced technology on light-duty gasoline vehicles and then applied those technologies to their heavy-duty gasoline applications. We expect that manufacturers will take this same approach to meeting the 2008 heavy-duty gasoline standards, through the application of technology developed to meet light-duty Tier 2 standards beginning in the 2004 model year.

Improved calibration and systems management will be critical in optimizing the performance of the engine with the advanced catalyst system. Precise air/fuel control must be tailored for emissions performance and must be optimized. Calibration refinements may also be needed for EGR system optimization and to reduce cold start emissions through methods such as spark timing retard. We also project that electronic control modules with expanded capabilities will be needed on some vehicles and engines.

We also expect increased use of other technologies in conjunction with those described above. We expect some increased use of air injection to improve upon cold start emissions. We may also see air-gap manifolds, exhaust pipes, and catalytic converter shells as a means of improving upon catalyst light-off times, thereby reducing cold start emissions. Other, non-catalyst related improvements to gasoline emission control technology include higher speed computer processors which enable more sophisticated engine control algorithms and improved fuel injectors providing better fuel atomization and improved fuel combustion.

For engine certified systems, the biggest concern will be the thermal durability of the catalysts due to the heavier loads typical of the larger, more commonly engine certified, systems. However, there is less emphasis on cold start emissions on the engine certification test procedure than the chassis test procedure. As a result, there may be less use of close-coupled catalysts for engine certified systems, although we have assumed the same implementation of that technology for vehicles and engines.

Catalyst system durability is a key issue in the feasibility of the standards. Historically, catalysts have deteriorated when exposed to very high temperatures and this has long been a concern for heavy-duty work vehicles. Manufacturers have often taken steps to protect catalysts by ensuring exhaust temperatures remain in an acceptable range. Catalyst technologies in use currently are much improved over the catalysts used only a few years ago. The improvements have come with the increased use of palladium, which has superior thermal stability, and through much improved washcoat technology. The use of rhodium with palladium will also enhance performance of the catalyst. The catalysts have been shown to withstand temperatures typically experienced in heavy-duty applications. Nonetheless, as a worst-case assumption, we are

assuming that 2008 model year heavy-duty gasoline vehicles and engines will require up to a 25 percent increase in precious metal loadings over the estimated 2005 loadings (i.e., 5 g/L versus 2005 levels of 4 or 4.5 g/L) to ensure acceptable catalyst durability characteristics while meeting the standards. Further, we are assuming that catalyst volumes will increase to roughly coincide with engine displacement volume. As a result of the greater catalyst volume, and the greater PGM loading per unit volume, we are assuming considerably more precious metals for greater durability. These costs are reflected in the cost estimates in Chapter V.

We believe that manufacturers will be able to achieve the 2008 standards by optimizing all of these technologies. Current catalyst systems using some of these technologies have already shown potential to reduce emissions to close to the required levels. Some current California vehicles in the 8,500-10,000 pound range are certified to levels below 0.2 g/mile NO_x. The California Air Resources Board tested an advanced catalyst system on a vehicle loaded to a test weight comparable to a heavy-duty vehicle test weight and achieved NO_x and NMOG levels of 0.1 g/mile and 0.16 g/mile, respectively. Furthermore, the California vehicle with the advanced catalyst had not been optimized as a system to take full advantage of the catalyst's capabilities.

In a light-duty truck technology demonstration program performed for our Tier 2 rulemaking effort, we found that a combination of calibration changes and improvements to the catalyst system resulted in heavy light-duty truck (LDT4) NO_x emission levels well below, and NMHC/NMOG emissions slightly below, the Tier 2 intermediate useful life standards (0.05 g/mi NO_x and 0.075 g/mi NMOG).¹²⁹ The catalyst improvements consisted of increases in volume and precious metal loading, and higher cell-densities than those found in the original hardware. Figures III.B-2 and III.B-3 show the results of our testing on a Ford Expedition and a Chevrolet Silverado, respectively.¹³⁰ These figures demonstrate the dramatic improvements in emissions that are possible with even the fairly simple enhancements that were done in a very short time as part of this test program.

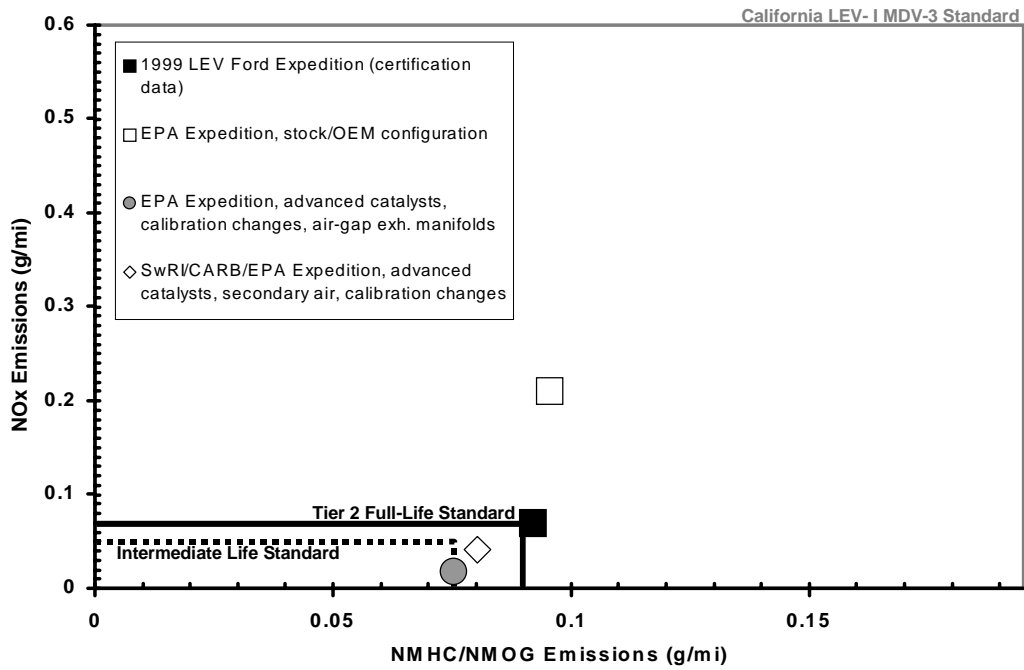


Figure III.B-2. Emissions after an equivalent of 50,000 miles for various tested configurations of Ford Expedition LDT4 SUVs with 5.4L V8 engines

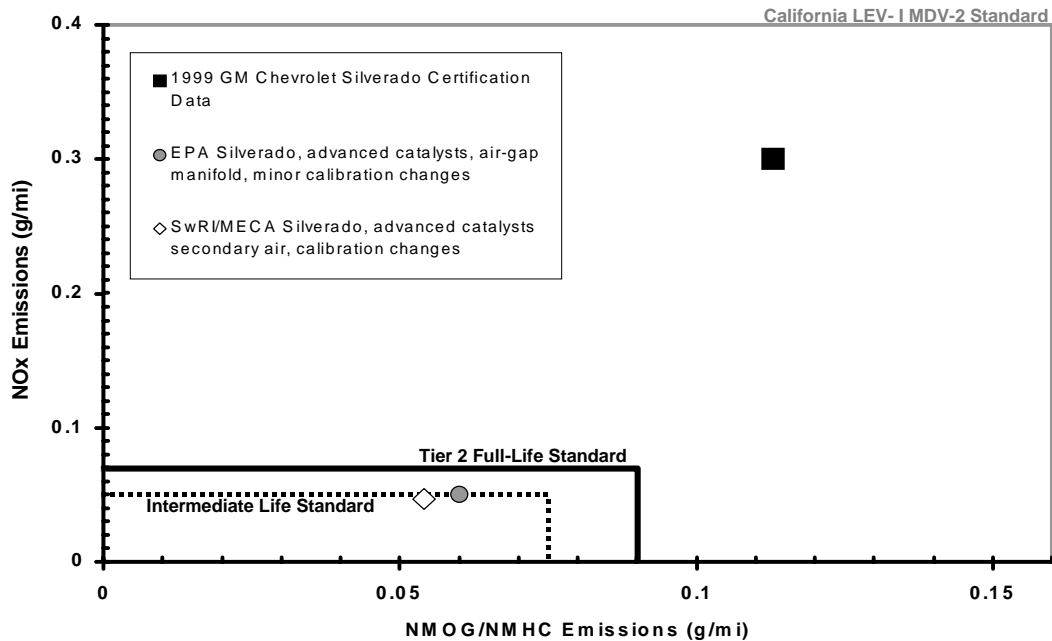


Figure III.B-3. Emissions after an equivalent of 50,000 miles for various tested configurations of 1999 GM Chevrolet Silverado LDT3 pickups with 5.3L V8 engines

The most significant difference between LDT4s (the heaviest of the light-duty classification) and medium-duty passenger vehicles (MDPV), which had been heavy-duty gasoline vehicles prior to our Tier 2 rule, is that MDPVs have a vehicle weight up to 800 pounds more than LDT4s. MDPVs will also be typically equipped with larger displacement engines. The potential impact of these differences is higher engine-out emissions than typical LDT4s. These higher engine out emissions may be expected due to both the larger engine displacement, and the greater load that the engine will be operated under due to the extra weight. However, neither of these preclude manufacturers from applying the same basic emission control technologies and strategies as used by light-duty vehicles and trucks. The only difference will likely be the need for larger catalysts with higher precious metal loadings than found in current systems.

We believe that the test weight difference should not have a significant impact on the emission levels to which these vehicles can be certified. We have tested a Ford Excursion and

baseline results with a green (i.e., “new”) catalyst indicate that emission levels are approximately at, or slightly above, the 2008 heavy-duty standards. We tested the Excursion at loaded vehicle test weight (curb weight + 300 lb, or ~7400 pounds) and again at adjusted loaded vehicle weight (curb + half payload, or ~8000 pounds) and found that the engine-out and tailpipe emission results for NMHC and NO_x were within ten percent for the two test weights. In other words, the additional weight (approximately 600 lbs) had no impact on emission performance. This is borne out in the data shown in Table III.B-3, which shows that the DaimlerChrysler 8.0L engine used in the Ram 2500 Pickup (GVWR = 8,800 lbs) and the Ram 3500 Pickup (GVWR = 10,500 lbs) both have very similar emission levels despite having different payloads and, therefore, different test weights. In fact, the heavier vehicle actually had slightly lower emissions. This is also true with the Ford 6.8L engine used in the E350 (GVWR = 9300 lbs) and in the F350 (GVWR = 11,000 lbs); both of these vehicles have essentially the same emission levels. This is significant because the majority of the heavy-duty vehicles falling under the 2008 heavy-duty standards are large panel vans and pick-up trucks which typically weigh the same or less than MPDVs.

Additionally, we believe that the 2008 standards will require manufacturers to focus some effort on engine-out emissions control, and that engine-out NO_x levels in the 6 to 8 g/bhp-hr are reasonably achievable.^{bb} Since some engines are already in this range, we believe that future engines may even deliver lower engine out emissions. Current HD gasoline engines rely very little on EGR. Recalibration of engine systems, including the EGR system and perhaps some modest hardware changes to those systems, will be necessary. EGR plays a key role in reducing engine-out NO_x and system redesign may allow more effective use of this technology.

Lastly, the proposed averaging, banking, and trading (ABT) program can be an important tool for manufacturers in implementing the new standards. The ABT program will allow manufacturers to comply with the more stringent standards by introducing emissions controls over a longer period of time, as opposed to doing so during one or two model years. Manufacturers plan their product introductions well in advance. With ABT, manufacturers can better manage their product lines so that the new standards do not interrupt their product introduction plans. Also, the program allows manufacturers to focus on higher sales volume vehicles first to earn credits and then use those credits for low sales volume vehicles. We believe manufacturers have significant opportunity to earn credits in the pre-2008 time frame by selling their California LEV II certified vehicles nationwide. Further, we are allowing manufacturers to apply credits earned on vehicle sales to their engine sales, and vice versa, although a 20 percent

^{bb} Note that the Phase 1 HD rule requires that diesel engines meet a standard of 2.5 g/bhp-hr NO_x+NMHC, of which we believe 2.2 to 2.3 grams will be NO_x emissions. That emission level will not require exhaust emission control technology (i.e., catalysts) and will instead be met through use of cooled EGR. In effect, the 2.2 gram NO_x level is an engine-out NO_x level that will be achieved by diesel engines complying with that standard.

discount will apply.^{cc} This ability to use credits across the vehicle/engine categories provides even greater incentive to introduce LEV II vehicles earlier than 2008 to earn credits that can be applied to the lower sales volume engine certified systems. This should provide attractive cost efficiencies to manufacturers while having no negative effects on, and perhaps even improving, air quality.

This discussion highlights our belief that there are numerous proven and existing technologies available that will allow heavy-duty gasoline vehicles to meet our 2008 heavy-duty gasoline exhaust emission standards. Therefore, we believe that these technologies, combined with low sulfur gasoline, ABT, and considerable leadtime before the 2008 model year implementation, will make the 2008 standards technologically feasible for heavy-duty gasoline vehicles.

5. The 2008 Heavy-Duty Gasoline Evaporative Emission Standards

The new evaporative emission standards for heavy-duty vehicles and engines are shown in Table III.B-5. These standards will apply to heavy-duty gasoline-fueled vehicles and engines, and methanol-fueled heavy-duty vehicles and engines. Consistent with existing standards, the standard for the two day diurnal plus hot soak test sequence would not apply to liquid petroleum gas (LPG) fueled and natural gas fueled HDVs.

**Table III.B-5. New Heavy-Duty Evaporative Emission Standards^A
(grams per test)**

<i>Category</i>	<i>3 Day Diurnal + Hot Soak</i>	<i>Supplemental 2 Day Diurnal + Hot Soak^B</i>
8,500 - 14,000 lbs	1.4	1.75
>14,000 lbs	1.9	2.3

^A To be implemented on the same schedule as the gasoline engine and vehicle exhaust emission standards shown in Table III.B-2. These new standards do not apply to medium-duty passenger vehicles, and do not apply to diesel fueled vehicles and engines.

^B Does not apply to LPG or natural gas fueled HDVs.

^{cc} As explained in the preamble to this rule, we believe this 20 percent discount is necessary to account for the uncertainty in converting between g/mi standards and g/bhp-hr standards.

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These new standards represent more than a 50 percent reduction in the numerical standards as they exist today. The Phase 1 heavy-duty rule made no changes to the numerical value of the standard, but it did put into place new evaporative emission test procedures for heavy-duty complete gasoline vehicles.^{dd} For establishing evaporative emission levels from complete heavy-duty vehicles, the standards shown in Table III.B-5 presume the test procedures required in the Phase 1 heavy-duty rule.

The new standards for 8,500 to 14,000 pound vehicles are consistent with the Tier 2 standards for medium-duty passenger vehicles (MDPV). MDPVs are of consistent size and have essentially identical evaporative emission control systems as the remaining work-oriented HDVs in the 8,500 to 10,000 pound weight range. Therefore, the evaporative emission standards should be equivalent. We are requiring those same standards for the 10,000 to 14,000 pound HDVs because, historically, the evaporative emission standards have been consistent throughout the 8,500 to 14,000 pound weight range. The HDVs in the 10,000 to 14,000 pound range are essentially equivalent in evaporative emission control system design as the lighter HDVs; therefore, continuing this historical approach is appropriate.

The evaporative emission standards for the over 14,000 pound HDVs are slightly higher because of their slightly larger fuel tanks and for non-fuel emissions related to larger vehicle sizes. This is consistent with past evaporative emission standards. The levels for the over 14,000 pound HDVs maintains the same ratio relative to the 8,500 to 14,000 pound HDVs as exists with current evaporative standards. To clarify, the current standards for the 3 day diurnal test are 3 and 4 grams/test for the 8,500 to 14,000 and the over 14,000 pound categories, respectively. The ratio of 3:4 is maintained for the new 2008 standards, 1.4:1.9.

The new standard levels are slightly higher than the California LEV-II standard levels. The California standard levels are 1.0 and 1.25 for the 3-day and the 2-day tests, respectively. However, federal vehicles are certified using the higher-volatility federal test fuel.^{ee} Arguably, the federal and California evaporative emission standards are equivalent in stringency despite the difference in standard levels.

^{dd} The test procedure changes codify a commonly approved waiver allowing heavy-duty gasoline vehicles to use the light-duty driving cycle for demonstrating evaporative emission compliance. The urban dynamometer driving schedule (UDDS) used for heavy-duty vehicles is somewhat shorter than that used for light-duty vehicles, both in terms of mileage covered and minutes driven. This results in considerably less time for canister purge under the heavy-duty procedure than under the light-duty procedure. We recognize this discrepancy and have routinely provided waivers under the enhanced evaporative program that allow the use of the light-duty procedures for heavy-duty certification testing. This is consistent with CARB's treatment of equivalent vehicles. (See 65 FR 59896, October 6, 2000.)

^{ee} The federal test fuel specification for fuel volatility, the Reid Vapor Pressure, is 8.7 to 9.2 psi. The California test fuel specification is 6.7 to 7.0 psi.

The new evaporative emission standards are to be implemented on the same schedule as the gasoline engine and vehicle exhaust standards shown in Table III.B-2. This will allow manufacturers to plan any needed changes to new vehicles at the same time, although it is not necessary that the exhaust and evaporative standards be phased-in on the same vehicles and engines. Also, the revised durability provisions finalized in the Tier 2 rule will apply. These provisions require a durability demonstration using fuel containing at least 10 percent alcohol. Alcohol can break down the materials used in evaporative emission control systems. This provision should not have an impact on the feasibility of the new standards.

6. Technological Feasibility of the 2008 Heavy-Duty Gasoline Evaporative Emission Standards

The new evaporative emission standards appear to be feasible now. Many designs have been certified that already meet these standards. A review of 1998 through 2000 model year certification data indicates that nearly all evaporative system families in the 8,500 to 14,000 pound range comply with the proposed 1.4 g/test standard, while all evaporative system families in the over 14,000 pound range comply with the proposed 1.9 g/test standard. Table III.B-6 summarizes the 1998 through 2000 model year evaporative emission certification data.

Table III.B-6. 1998-2000 Model Year Evaporative Emission Certification Data (grams/test)

<i>Manufacturer</i>	<i>Category (GVWR)</i>	<i>3 Day Diurnal Emissions (grams/test)</i>
DaimlerChrysler	<14k	0.74
		0.64
		0.64
		1.01
		1.06
Ford	<14k	1.17
		1.80
	>14k	1.17
		1.80
General Motors	<14k	0.67
		0.78
		0.85
		1.03
		1.29
		1.57
		1.69
		1.74
	>14k	0.67
		0.73
		0.85
		1.03
		1.29
		1.57
1.69		
1.74		

There are two approaches to reducing evaporative emissions for a given fuel. One is to minimize the potential for permeation and leakage by reducing the number of hoses, fittings and connections. The second is to use less permeable hoses and lower loss fittings and connections. Manufacturers are already employing both approaches. Fluoropolymer materials can be added as liners to hose and component materials to yield large reductions in permeability over such conventional materials as monowall nylon. In addition, fluoropolymer materials can greatly reduce the adverse impact of alcohols in gasoline on permeability of evaporative components, hoses and seals. Alcohols, present in about 10 percent of gasoline sold in the U.S., cause swelling of conventional materials which leads to increases in permeability and can also lead to

tearing and leakage in situations where the materials are constrained in place, such as with gaskets and O-rings. Due to the common presence of alcohols such as ethanol in the gasoline pool, and its adverse affect on materials and emissions durability, we believe materials such as those discussed above are necessary to ensure that the benefits are captured in-use. Rather than requiring new application of these materials, our new evaporative standards will simply ensure their consistent and continued use on most engines by discouraging manufacturers from switching to cheaper materials or designs to take advantage of the large safety margins they have under current standards.

Additionally, most manufacturers are moving to “returnless” fuel injection systems. Through more precise fuel pumping and metering, these systems eliminate the return line in the fuel injection system. The return line carries unneeded fuel from the fuel injectors back to the fuel tank. Because the fuel injectors are in such close contact with the hot engine, the fuel returned from the injectors to the fuel tank has been heated. This returned fuel is a significant source of fuel tank heat and vapor generation. The elimination of the return line also reduces the total length of hose on the vehicle through which vapors can permeate, and it reduces the number of fittings and connections through which fuel can leak.

Steel fuel tanks and steel fuel lines have essentially zero losses due to permeation, but are vulnerable to leakage at joints and interfaces. Manufacturers are moving toward plastic fuel tanks for their lighter weight and greater ability to be molded to odd shapes. However, plastic tanks are permeable and are also susceptible to seepage and higher permeability at areas where connections and welds are made. Materials and manufacturing techniques exist to reduce these losses.

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Chapter IV: Fuel Standard Feasibility

A. Feasibility of Removing Sulfur from Highway Diesel Fuel

1. Sources of Diesel Fuel Sulfur

The primary sources of sulfur in diesel fuel are the sulfur-containing compounds which occur naturally in crude oil.¹ Depending on the source, crude oil contains anywhere from fractions of a percent of sulfur, such as less than 0.05 weight percent (500 ppm) to as much as several percent.¹ The average amount of sulfur in crude oil refined in the U.S. is about one percent.² Most of the sulfur in crude oil is in the heaviest boiling fractions. Since most of the refinery blendstocks that are used to manufacture diesel fuel come from the heavier boiling components of crude oil, they contain substantial amounts of sulfur.

The diesel fuel produced by a given refinery is composed of one or more blendstocks from the crude oil fractionation and conversion units at the refinery. Refinery configuration and equipment, and the range and relative volumes of products manufactured (the product slate) can significantly affect the sulfur content of diesel fuel. The diagram on the following page illustrates the configuration and equipment used at a typical complex refinery in the U.S.

¹ Additives that contain sulfur are sometimes intentionally added to diesel fuel. For a discussion how the addition of these additives will be affected under this program, see Section IV.D.5.

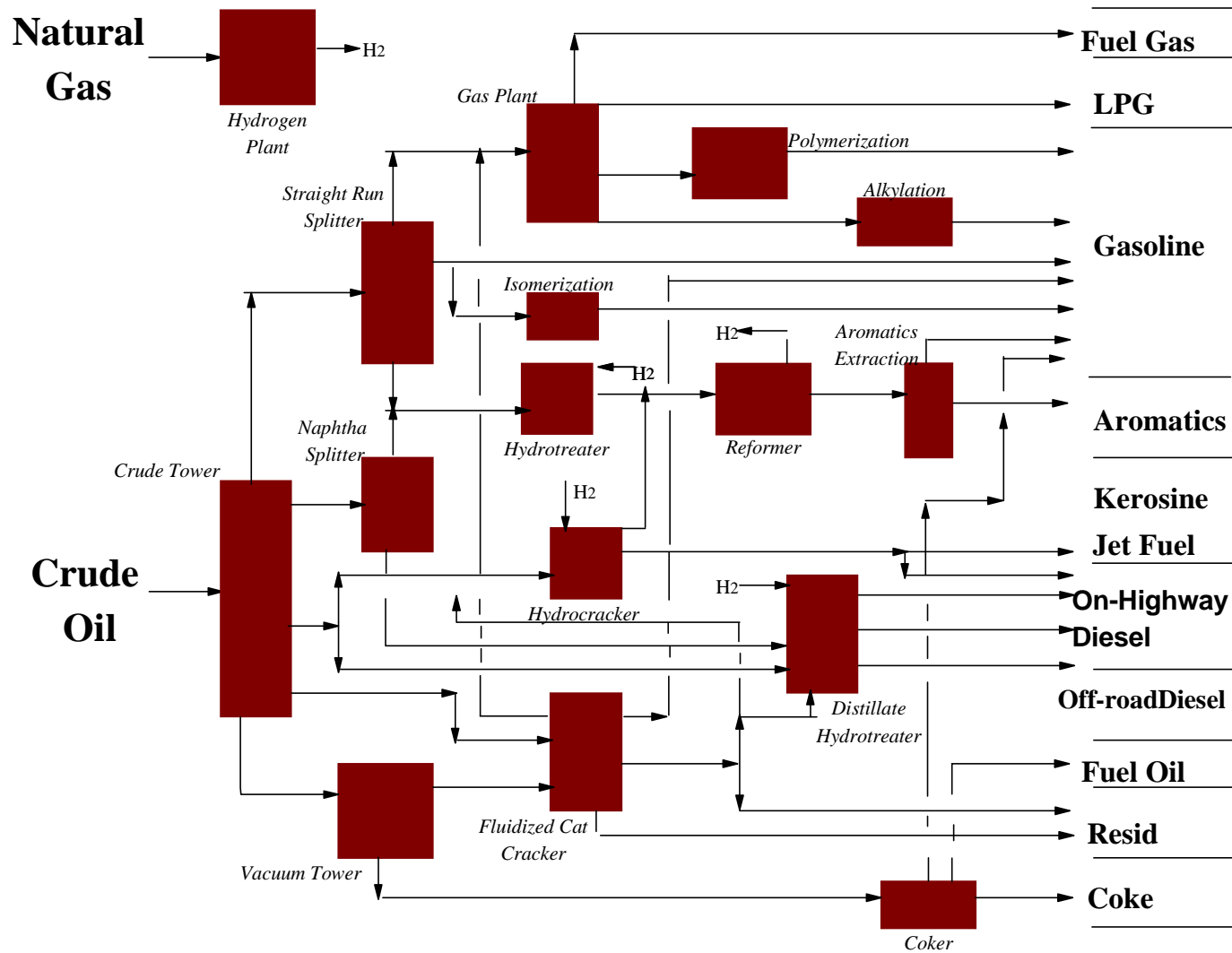


Figure IV.A-1. Diagram of a Typical Complex Refinery

Refineries differ from the model in the preceding diagram depending on the range of crude oils used, and their product slate. For example:

- Refiners that process heavier crude oils are more likely to operate coker and/or hydrocracker units.
- Refinery streams that can be used to manufacture diesel fuel can also be used in the manufacture of heating oil, kerosene and jet fuel. Much of the distillate product from the hydrocracker is often blended into jet fuel rather than diesel fuel.

On an aggregate basis, most of the highway diesel fuel volume manufactured in the U.S. comes from the straight-run product from the crude fractionation tower (called straight run). Most of the remainder comes from the fluid catalytic cracker (FCC) conversion unit (called light cycle oil). The remaining small fraction of diesel fuel volume comes from a coker conversion unit (called light coker gas oil), or from the hydrocracker conversion unit (called hydrocrackate).

To comply with the current federal regulatory requirement on the sulfur content of highway diesel fuel (500 ppm cap), the blendstock streams from these process units are typically further processed to reduce their sulfur content. Desulfurization of highway diesel blendstocks is currently accomplished in fixed-bed hydrotreaters that operate at moderate pressures (500-700 psi), with a few exceptions at higher pressures such as the small portion of highway diesel which comes from hydrocrackers. Most of the low-sulfur diesel blendstocks come from such hydrotreaters. However, a small amount of low-sulfur diesel also comes from hydrocrackers. The sulfur levels of the various highway diesel blendstocks and the fraction of the total volume of highway diesel fuel that comes from each blendstock varies considerably from refinery to refinery. A recent survey conducted by the American Petroleum Institute (API) and National Petroleum Refiners Association (NPRA) in 1996 examined the typical blendstock properties for the U.S. highway diesel pool as a whole.³ The results of this survey are contained in the following tables (IV.A-1 and IV.A-2).

**Table IV.A-1. Volume Fraction of U.S. Highway Diesel Pool
from each Blendstock Component⁴**

<i>Diesel Blendstock</i>	<i>Percent of U.S. Highway Diesel Fuel Pool per Blendstock Boiling Fraction</i>				
	<i>Naphtha</i>	<i>Light Distillate</i>	<i>Heavy Distillate</i>	<i>Light Gas Oil</i>	<i>All Boiling Fractions Combined</i>
Straight Run	0.1	6.4	4.9	1.0	12.4
Hydrotreated Straight Run	0.3	8.1	41.2	2.3	51.9
Cracked Stock	-	0.1	0.8	2.2	3.1
Hydrotreated Cracked Stock	-	2.1	15.6	1.7	19.4
Coker Gas Oil	-	-	1.0	-	1.0
Hydrotreated Coker Gas Oil	0.1	2.1	3.7	2.3	8.2
Hydrocrackate	-	1.3	2.7	-	4.0

Table IV.A-2. Sulfur Levels of Highway Diesel Blendstocks (CA Excluded)⁵

Diesel Blendstock	Sulfur Content (ppm) by Boiling Fraction of the Blendstock ^A				
	Naphtha	Light Distillate	Heavy Distillate	Light Gas Oil	All Boiling Fractions Combined ^B
Straight Run	827	1,770	2,269	4,980	2,218
Hydrotreated Straight Run	362	119	394	548	358
Cracked Stock	-	2,219	2,892	6,347 ^C	5,322
Hydrotreated Cracked Stock	18	37	939	1,306 ^C	874
Coker Gas Oil	540	1,800	3,419	-	3,419
Hydrotreated Coker Gas Oil	8 ^C	25	310	400	258
Hydrocrackate	-	12	120	-	85

- A The boiling ranges that define the four different boiling fractions of each diesel blendstock (naphtha, light distillate, heavy distillate, and light gas oil) varied somewhat from refiner to refiner. There was also definitional overlap in the boiling ranges provided by refiners.
- B These values were derived by weighting the values for the four boiling fractions by the fraction they represent of the highway diesel fuel blendstock (see Table IV-1).
- C Indicates properties that were not reported in the refiner survey. These values were calculated using the reported sulfur contents of like boiling fractions in other diesel blendstocks by assuming the same relative sulfur levels between boiling fractions. This was necessary to allow the calculation of the sulfur content of the blendstock as a whole.

As shown in Table IV.A-1, approximately 80 percent of all blendstocks used to manufacture highway diesel fuel outside of California are hydrotreated to reduce their sulfur content. Hydrocrackate is desulfurized to a substantial extent as a necessary element of the hydrocracking process and is not further processed in a hydrotreater. The table also shows that approximately 16 percent of highway diesel fuel comes from nonhydrotreated blendstocks.

The blendstocks used to manufacture highway diesel fuel used in California differ from the rest of the nation due to the unique requirements of the California market and California's specific regulatory requirements. As a result, California's highway diesel fuel averages 140 ppm sulfur.⁶ Highway diesel fuel used in California is made primarily from hydrocrackate and hydrotreated straight run in roughly equal proportions, with a small volume fraction of

hydrotreated cracked stock and hydrotreated coker gas oil. No high-sulfur containing blendstocks are used in the manufacture of California highway diesel fuel. California diesel fuel requirements include a limit on aromatics content which limits the amount of light-cycle oil (LCO) and light-coker gas oil (LCGO) that can be used in the manufacture of California highway diesel fuel. LCO and LCGO have a high aromatics content which is not reduced by desulfurization.

2. Current Levels of Sulfur in Highway Diesel Fuel

To determine the most cost-effective sulfur removal methods, it is important to evaluate the amount of sulfur currently in highway diesel fuel. EPA set standards for highway diesel fuel quality in 1990 (55 FR 34120, August 21, 1990). These standards have been effective since 1993. The standards limit the sulfur concentration in fuel to a maximum of 500, compared to a pre-regulation average of 2500 ppm. They also protect against a rise in the fuel's aromatics content from then-existing levels by setting a minimum cetane index of 40 (or, alternatively, a maximum aromatics level of 35 volume percent).

California set more stringent standards in 1988 for motor vehicle diesel fuels used in the South Coast air basin.⁷ These standards took effect statewide in 1993. They apply to both highway and off-highway fuels (excluding marine and locomotive use), and limit sulfur levels to 500 ppm and aromatics levels to 10 volume percent, with some flexibility provisions to accommodate small refiners and alternative formulations. Under the provisions for alternate formulations, fuel manufacturers have certified highway diesel fuel for use in California with a lower maximum sulfur content than 500 ppm (California highway diesel fuel actually averages 140 ppm) and a higher maximum aromatics content than 10 percent.

Alaska and certain U.S. territories currently have an exemption from federal highway diesel fuel requirements. In these areas, the) an ASTM (the American Society for Testing and Materials) specification on the maximum allowed sulfur content of diesel fuel (5,000 ppm) applies.⁸ These regulatory and industry criteria set the upper bound on the sulfur content of highway diesel fuel in the U.S.

To enable our cost analysis, we compiled the data by various regions called Petroleum Administrative Districts for Defense (PADDs), as well as for California and the country as a whole.⁹ The PADD regions are illustrated in the following figure (IV.A-2).

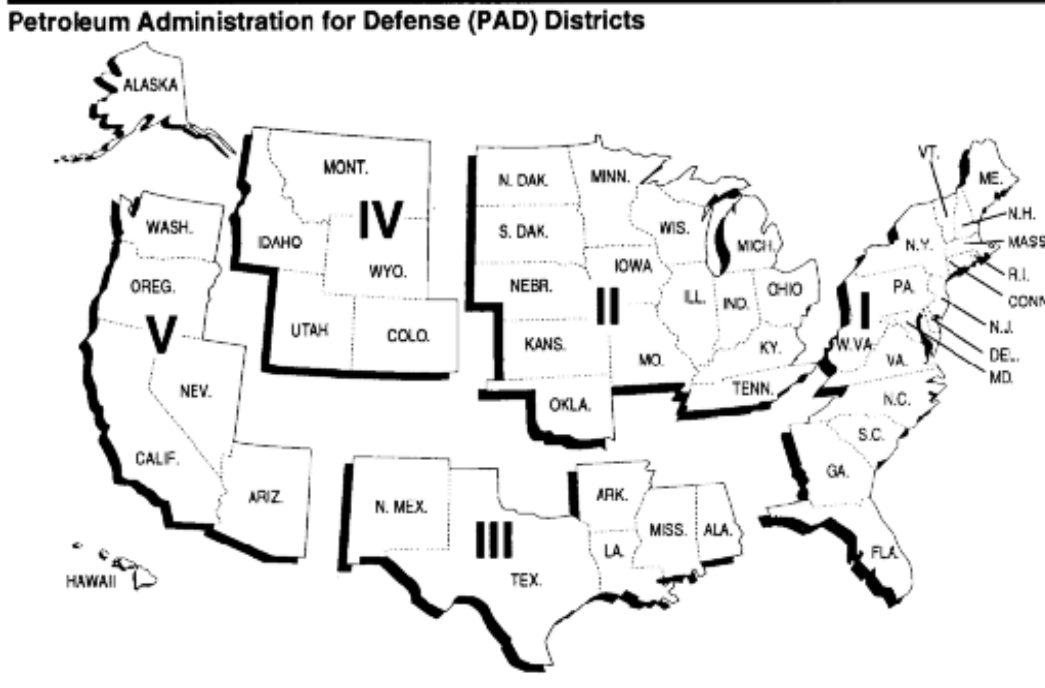


Figure IV.A-2. Map of U.S. Petroleum Administrative Districts for Defense

Our evaluation revealed relatively little difference in the sulfur content of highway diesel fuel in PADDs 1, 2, 3, and 4. The sulfur content of highway diesel fuel in California is considerably lower than that in the rest of the nation due to regulatory requirements specific to California. The sulfur content of diesel fuel in PADD 5 outside of California and Alaska, although higher than that within California, is lower than that in PADDs 1 through 4. This is due to the fact that a large fraction of the highway diesel fuel used in PADD 5 outside of California and Alaska is manufactured by refineries that are configured primarily to supply lower-sulfur diesel fuel to the California market. Alaska currently has an exemption from federal highway diesel sulfur requirements. Please refer to Chapter IX for a discussion of diesel fuel sulfur levels in Alaska.

Table IV.A-3. Average Highway Diesel Fuel Sulfur Levels by Geographic Area

	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5 O-CA&AK*</i>	<i>CA</i>	<i>U.S. Avg.*</i>
Sulfur Content (PPM)	340	350	360	330	280	140	340

* Outside of California and Alaska.

3. Current Levels of Other Fuel Parameters in Highway Diesel Fuel

The refinery process options which could be used reduce the sulfur content of highway diesel to under 15 ppm have the potential to affect other fuel parameters as well. Highway diesel fuel is required to meet specifications on a range of fuel parameters.¹⁰ If process changes made to comply with the proposed cap on sulfur content adversely affect other fuel parameters, refiners may need to take additional steps to ensure that these other parameters meet specifications. Thus, to determine the most cost-effective sulfur removal methods, it is also important to evaluate current levels of the other fuel parameters which might be affected by refinery process changes to meet the sulfur cap. Data on the current distillation characteristics, API gravity, pour point, natural cetane level, and aromatics content of diesel fuel blendstocks are contained in the following tables (IV.A-4, IV.A-5, and IV.A-6).

Table IV.A-4. Distillation Characteristics of Diesel Blendstocks (CA Excluded)¹¹

Blendstock	Distillation Fraction	Distillation (°F)				
		T10	T30	T50	T70	T90
Straight-Run	Naphtha	325	349	393	422	452
	Light Distillate	360	394	421	443	477
	Heavy Distillate	466	510	540	567	601
	Light Gas Oil	421	456	547	575	618
Hydrotreated Straight Run	Naphtha	296	375	405	432	467
	Light Distillate	383	412	429	454	484
	Heavy Distillate	431	492	543	576	621
	Light Gas Oil	457	528	584	-	595
Cracked Stock	Naphtha	-	-	-	-	-
	Light Distillate	346	357	369	384	408
	Heavy Distillate	488	-	526	541	637
	Light Gas Oil	-	508	547	599	666
Hydrotreated Cracked Stock	Naphtha	284	-	310	-	351
	Light Distillate	345	360	385	440	508
	Heavy Distillate	448	501	-	565	613
	Light Gas Oil	457	524	534	-	634
Coker Gas Oil	Naphtha	237	-	314	-	399
	Light Distillate	369	382	394	410	436
	Heavy Distillate	454	-	501	531	561
	Light Gas Oil	-	-	-	-	-
Hydrotreated Coker Gas Oil	Naphtha	188	210	245	275	305
	Light Distillate	359	375	463	494	580
	Heavy Distillate	460	-	504	534	594
	Light Gas Oil	521	564	599	-	628
Hydrocrackate	Naphtha	-	-	-	-	-
	Light Distillate	357	393	435	459	503
	Heavy Distillate	433	501	528	556	617
	Light Gas Oil	-	-	-	-	-

Table IV.A-5. Properties of Diesel Blendstocks (CA Excluded)¹²

<i>Blendstock</i>	<i>Distillation Fraction</i>	<i>Aromatics (Vol %)</i>	<i>Cetane # (Unadditized)</i>	<i>API Gravity</i>	<i>Pour Point (°F)</i>
Straight-Run	Naphtha	-	-	50.0	70 (additized)
	Light Distillate	15.9	40.3	42.2	-
	Heavy Distillate	15.5	-	35.2	-
	Light Gas Oil	-	45.0	30.3	11
Hydrotreated Straight Run	Naphtha	-	-	47.1	-
	Light Distillate	18.6	44.5	42.9	-
	Heavy Distillate	31.0	50.4	34.4	-
	Light Gas Oil	-	-	29.9	3
Cracked Stock	Naphtha	-	-	-	-
	Light Distillate	40.2	-	33.1	-
	Heavy Distillate	-	-	26.8	-
	Light Gas Oil	-	-	22.3	-
Hydrotreated Cracked Stock	Naphtha	-	-	52.6	-
	Light Distillate	19.0	42.7*	45.0	-
	Heavy Distillate	45.0	44.1*	30.7	-
	Light Gas Oil	-	-	-	-
Coker Gas Oil	Naphtha	8.0	-	51.7	-
	Light Distillate	-	-	42.4	-
	Heavy Distillate	-	-	32.2	-
	Light Gas Oil	-	-	-	-
Hydrotreated Coker Gas Oil	Naphtha	-	-	-	-
	Light Distillate	22.1	45.3	43.1	-
	Heavy Distillate	25.1	-	34.8	-
	Light Gas Oil	-	36.1	29.9	-
Hydrocrackate	Naphtha	-	-	-	-
	Light Distillate	-	-	41.8	-
	Heavy Distillate	24.2	50.2	32.9	-
	Light Gas Oil	-	-	-	-

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- * While these values are quoted directly from the API/NPRA survey, they are high compared to values found in other information sources. We understand the cetane number of light cycle oil is normally in the 20s.

Table IV.A-6. Average Highway Diesel Fuel Parameter Levels by Geographic Area¹³

<i>Fuel Parameter</i>	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5 (OC)*</i>	<i>CA</i>	<i>U.S. (OC)*</i>	
API Gravity	34.6	34.2	34.3	36.2	33.8	33.6	34.4	
Cetane Number Unadditized	-	42.9	43.8	-	46.5	42.6	44.1	
Cetane Additive (ppmv)	0	83	2	12	0	183	27	
Cetane Number [additized]	-	-	-	-	-	-	-	
Pour Point (°F) [additized]	[10]	[10]	[2]	0	[2]	6	[5]	
Pour Point Depressant Additive (ppmw)	7	47	7	11	0	0	19	
Distillation (°F)	T10	426	427	436	405	432	447	431
	T30	458	470	478	435	472	-	471
	T50	497	505	514	495	521	525	510
	T70	549	549	557	519	554	-	551
	T90	609	600	610	598	611	612	606
Aromatics (Vol %)	28.9	25.8	37.0	27.1	-	28.8	32.3	

* Outside of California

4. Overview of Diesel Fuel Sulfur Control

As mentioned in Section A.1., the sulfur in diesel fuel comes from the crude oil processed by the refinery. One way to reduce the amount of sulfur in diesel fuel, therefore, is to process a crude oil that is lower in sulfur. Some refiners already do this. Others could switch to low or at least lower sulfur crude oils. However, there is limited capability worldwide to produce low sulfur crude oil. While new oil fields producing light, sweet crude oil are still being discovered, most of the new crude oil production being brought on-line is heavier, more sour (i.e., higher

sulfur) crude oils. The incentive to use low sulfur crude oils has existed for some time and low sulfur crude oils have traditionally commanded a premium price relative to higher sulfur crude oils. While a few refiners with access to lower sulfur crude oil could potentially reduce their diesel sulfur levels in this way, it is not feasible for most, let alone all U.S. refiners to switch to low sulfur crude oils to meet a tighter diesel fuel sulfur standard. In addition, while helpful, a simple change to a low sulfur crude oil would fall well short of compliance with the 15 ppm sulfur cap. Thus, this analysis will not assume that this broad approach could be used to meet the new highway diesel sulfur standard.

Another method to reduce diesel fuel sulfur is to chemically remove sulfur from the hydrocarbon compounds which comprise diesel fuel. This is usually accomplished through reaction with hydrogen at moderate to high temperature and pressure. A couple of specific examples of this process are hydrotreating and hydrocracking. Another process was announced recently which uses a moving bed catalyst to both remove and adsorb the sulfur using hydrogen at moderate temperature and pressure. There are other low temperature and pressure processes being developed, such as biodesulfurization, and chemical oxidation. Sulfur can be removed via these processes up front in the refinery, such as from crude oil, before being processed in the refinery into diesel fuel. Or, sulfur can be removed from those refinery streams which are to be blended directly into diesel fuel. Finally, another method to reduce diesel fuel sulfur is to shift sulfur-containing hydrocarbon compounds to other fuels produced by the refinery.

As discussed below, we expect that most of the sulfur reduction required by the sulfur cap standard will be chemical removal via hydrotreating. Thus, this section will begin with a relatively detailed discussion of the capabilities of this and similar processes. We also expect refiners to use the other methods to obtain cost effective sulfur reductions which will complement the primary sulfur reduction achieved via hydrotreating. These other methods, such as FCC feed hydrotreating, adsorption, biodesulfurization, chemical oxidation, and undercutting LCO, will be discussed following the primary discussion of distillate hydrotreating.

As mentioned above, this sulfur removal can occur either early or late in the refining process. The most practical place to remove sulfur early in the process is prior to the FCC unit. Hydrotreating feed to the FCC unit requires higher temperatures and pressures than hydrotreating distillate streams used to produce diesel fuel because FCC feed contains much larger and heavier molecules. Because of this, FCC feed hydrotreating is more expensive than distillate hydrotreating. We expect that most refiners will enhance or expand their current distillate hydrotreating capability to meet the sulfur cap, although the other benefits associated with FCC feed hydrotreating could lead some refiners to add this technology. The remaining discussion of hydrotreating will therefore begin with distillate hydrotreating, followed by a brief discussion of FCC feed hydrotreating.

5. Hydrotreating and Other Hydrogen-Based Processes Which Remove Sulfur

Hydrotreating and similar processes generally combine hydrogen with a hydrocarbon stream at high temperature and pressure in the presence of a catalyst. Refineries currently employ a wide range of these processes for a number of purposes. For example, naphtha (gasoline like material which itself does not meet gasoline specifications, such as octane level) being fed to the refinery reformer is always hydrotreated to remove nearly all sulfur, nitrogen and metal contaminants which would deactivate the noble metal catalyst used in the reforming process. Similarly, feed to the FCC unit is often hydrotreated to remove most of the sulfur, nitrogen and metal contaminants in order to improve the yield and quality of high value products, such as gasoline and distillate (distillate refers to a range of similar products including kerosene, diesel fuel, No. 2 heating oil and jet fuel), from the FCC unit. Nearly all refineries currently hydrotreat the refinery streams used to produce highway diesel fuel in order to remove much of the sulfur present and comply with the current 500 ppm sulfur cap. EPA expects that nearly all refiners will hydrotreat the naphtha produced by the FCC unit to remove most of the sulfur present to comply with the Tier 2 gasoline sulfur standards.¹⁴ These hydrotreating processes remove sulfur, nitrogen, metal and other contaminants from the hydrocarbon streams. They also can saturate some or most of the olefins present, depending on the process. However, they do not generally otherwise affect the chemical nature of the hydrocarbon compounds.

If the temperature or pressure is increased sufficiently, or a carbon-oriented catalyst is used, hydrotreating can more dramatically affect the chemical nature of the hydrocarbons, as well as remove contaminants. For example, through a process called hydrocracking, smaller, lighter molecules are created by splitting larger, heavier molecules. In the process, nearly all of the contaminants are removed and olefins and aromatics are saturated into paraffins and naphthenes. Outside the U.S., this process is commonly used to produce distillate from heavier, less marketable refinery streams. The production of distillate via hydrocracking to produce gasoline from poor quality distillate, such as LCO from the FCC unit.

A few refineries also currently hydrotreat their distillate more severely than is typical, but not as severe as hydrocracking. Their intent is to remove the sulfur, nitrogen and metallic contaminants and to also saturate most of the aromatics present. This is done primarily in Europe to meet very stringent specifications for both sulfur and aromatics applicable to certain diesel fuels and encouraged by reduced excise taxes. This severe hydrotreating process is also used in the U.S. to “upgrade” petroleum streams which are too heavy or too low in quality to be blended into the diesel pool, by cracking some of the material to lower molecular weight compounds and saturating some of the aromatics to meet the distillation and cetane requirements. A different catalyst which encourages aromatic saturation is used in lieu of one that simply encourages contaminant removal.

To meet the 15 ppm diesel sulfur cap, EPA expects refiners to focus as much as possible on sulfur removal. Other contaminants, such as nitrogen and metals, are already sufficiently removed by existing refinery processes. While saturation of aromatics generally improves diesel fuel quality, there is a significant additional cost involved, primarily the consumption of additional hydrogen. Consequently, we anticipate refiners will choose desulfurization processes that minimize the amount of aromatics saturation. Current diesel fuel already meets all applicable specifications, and hydrotreating to remove sulfur should not degrade quality, except possibly lubricity, as discussed in Section C. Thus, with this one exception, there should be no need to improve diesel fuel quality as a direct result of this new diesel sulfur standard. Should a refiner choose to do so, it would be to improve profitability,^b and not related to meeting the 15 ppm sulfur cap standard.

As mentioned above, this sulfur removal can occur either early or late in the refining process. The most practical place to remove sulfur early in the process is prior to the FCC unit. Hydrotreating feed to the FCC unit requires higher temperatures and pressures than hydrotreating distillate streams used to produce diesel because FCC feed contains much larger and heavier molecules. Because of this, FCC feed hydrotreating is more difficult and more expensive than distillate hydrotreating. We expect that most refiners will enhance or expand their current distillate hydrotreating capability to meet the 15 ppm sulfur diesel cap standard, although the other benefits associated with FCC feed hydrotreating will therefore begin with distillate hydrotreating, followed by a more brief discussion of FCC feed hydrotreating and other emerging diesel desulfurization technologies.

a. Fundamentals of Distillate Hydrotreating

Essentially all distillate hydrotreater designs follow the same broad format. Liquid distillate is heated and pumped to temperatures of 300-380°C and pressures of 500-700 psia with hydrogen and reacted over a catalyst. Hydrogen reacts with sulfur and nitrogen atoms contained in the hydrocarbon molecules, forming hydrogen sulfide and ammonia. The resulting vapor is then separated from the desulfurized distillate. The desulfurized distillate is usually simply mixed with other distillate streams in the refinery to produce diesel fuel and heating oil.

The vapor still contains a lot of valuable hydrogen, because the reaction requires the use of a significant amount of excess hydrogen to operate efficiently and practically. However, the vapor also contains a significant amount of hydrogen sulfide and ammonia, which inhibit the desulfurization and denitrogenation reactions and must be removed from the system. Thus, the

^b Refiners can choose to “upgrade” heavy refinery streams which do not meet the cetane and distillation requirements for highway diesel fuel. The process for doing so is also called ring opening, since one or more of the aromatic rings of heavy, aromatic molecules are opened up, improving the value of the stream. Upgrading the heavy refinery streams to highway diesel fuel improves the stream’s market price by 10 - 30 c/gal.

hydrogen leaving the reactor is usually mixed with fresh hydrogen and recycled to the front of the reactor for reaction with fresh distillate feed. However, by itself, this would cause a build up of hydrogen sulfide and ammonia in the system, since it would have no way to leave the system. In some cases, the hydrogen sulfide and ammonia are chemically scrubbed from the hydrogen recycle stream. In other cases, a portion of the recycle stream is simply purged from the system as a mixture of hydrogen, hydrogen sulfide and ammonia. The latter is less efficient since it leads to higher levels of hydrogen sulfide and ammonia in the reactor, but it avoids the cost of building and operating a scrubber.

Desulfurization processes in use today in the U.S. generally use only one reactor, due to the need to only desulfurize diesel fuel to 500 ppm or lower. However, a second reactor can be used, particularly to meet lower sulfur levels. Instead of liquid distillate going to the diesel fuel/heating oil pool after the first reactor, it would simply be mixed with fresh hydrogen and sent to the second reactor.

Traditional reactors are cocurrent in nature. The hydrogen is mixed together with the distillate at the entrance to the reactor and flow through the reactor together. Because the reaction is exothermic, heat must be removed periodically. This is sometimes done through the introduction of fresh hydrogen and distillate at one or two points further down the reactor. The advantage of cocurrent design is practical, it eases the control of gas-liquid mixing and contact with the catalyst. The disadvantage is that the concentration of hydrogen is the highest at the front of the reactor and lowest at the outlet. The opposite is true for the concentration of hydrogen sulfide. This increases the difficulty of achieving extremely low sulfur levels due to the low hydrogen concentration and high hydrogen sulfide concentration at the end of the reactor.

The normal solution to this problem is to design a counter-current reactor, where the fresh hydrogen is introduced at one end of the reactor and the liquid distillate at the other end. Here, the hydrogen concentration is highest (and the hydrogen sulfide concentration is lowest) where the reactor is trying to desulfurize the most difficult (sterically hindered) compounds. The difficulty of counter-current designs in the case of distillate hydrotreating is vapor-liquid contact and the prevention of hot spots within the reactor. The SynAlliance (consisting of ABB Lummus, Criterion Catalyst Corp., and Shell Oil Co.) has patented a counter-current reactor design called SynTechnology. With this technology, in a single reactor design, the initial portion of the reactor will follow a co-current design, while the last portion of the reactor will be counter-current. In a two reactor design, the first reactor will be co-current, while the second reactor will be counter-current.

ABB Lummus estimates that the counter-current design can reduce the catalyst volume needed to achieve 97 percent desulfurization by 16 percent relative to a co-current design.¹⁵ The impact of the counter-current design is even more significant when aromatics control (or cetane improvement) is desired in addition to sulfur control.

Sulfur containing compounds in distillate can be classified according to the ease with which they are desulfurized. Sulfur contained in paraffins or aromatics with a single aromatic ring are relatively easy to desulfurize. These molecules are sufficiently flexible so that the sulfur atom is in a geometric position where it can make physical contact with the surface of the catalyst. The more difficult compounds are contained in aromatics consisting of two aromatic rings, particularly dibenzothiophenes. Dibenzothiophene contains two benzene rings which are connected by a carbon-carbon bond and two carbon-sulfur bonds (both benzene rings are bonded to the same sulfur atom). This compound is essentially flat in nature and the carbon atoms bound to the sulfur atom hinder the approach of the sulfur atom to the catalyst surface. Despite this, today's catalysts are very effective in desulfurizing dibenzothiophenes, as long as only hydrogen is attached to the carbon atoms bound directly to the sulfur atom.

However, distillate can contain dibenzothiophenes which have methyl or ethyl groups bound to the carbon atoms which are in turn bound to the sulfur atom. These extra methyl or ethyl groups further hinder the approach of the sulfur atom to the catalyst surface. Dibenzothiophenes with such methyl or ethyl groups are commonly referred to as being sterically hindered. An example of a dibenzothiophene with a single methyl or ethyl group next to the sulfur atom is 4-methyl dibenzothiophene. An example of a dibenzothiophene with two methyl or ethyl groups next to the sulfur atom is 4,6-dimethyl dibenzothiophene. In 4,6-dimethyl dibenzothiophene, and similar compounds, the presence of a methyl group on either side of the sulfur atom makes it very difficult for the sulfur atom to react with the catalyst surface to assist the hydrogenation of the sulfur atom.

Most straight run distillates (or straight run light gas oil (SRLGO)) contains relatively low levels of these sterically hindered compounds. LCO contains the greatest concentration of sterically hindered compounds, while other cracked distillate streams from the coker and the visbreaker contain levels of sterically hindered compounds in concentrations between straight run and LCO. Thus, LCO is generally more difficult to desulfurize than coker distillate which is more difficult to treat than straight run distillate.¹⁶ In addition, cracked stocks, particularly LCO, have a greater tendency to form coke on the catalyst, which deactivates the catalyst and requires its replacement.

The greater presence of sterically hindered compounds in LCO is related to two fundamental factors. First, LCO contains much higher concentrations of aromatics than typical SRLGO.¹⁷ All sterically hindered compounds are aromatics. Second, the chemical equilibria existing in cracking reactions favors the production of sterically hindered dibenzothiophenes over unsubstituted dibenzothiophenes. For example, in LCO, methyl substituted aromatics are twice as prevalent as unsubstituted aromatics. Di-methyl aromatics are twice as prevalent as methyl aromatics, or four times more prevalent as unsubstituted aromatics. Generally, desulfurizing 4-methyl dibenzothiophene using conventional desulfurization is 6 times slower than desulfurizing similar non-sterically hindered molecules, while desulfurizing 4,6-dimethyl dibenzothiophene

using conventional desulfurization is 30 times slower. Slower reactions mean that either the volume of the reactor must be that much larger, or that the reaction must be somehow speeded up. The latter implies either a more active catalyst, higher temperature, or higher pressure. These alternatives will be discussed later below.

Because moderate sulfur reduction is often all that is required in distillate hydrotreating, catalysts have been developed which focus almost exclusively on contaminant removal. The most commonly used desulfurization catalyst consists of a mixture of cobalt and molybdenum (Co/Mo). These catalysts interact primarily with the sulfur atom and encourage the reaction of sulfur with hydrogen.

Other catalysts have been developed which encourage the saturation (hydrogenation) of the aromatic rings. As mentioned above, this generally improves the quality of the diesel fuel produced from this distillate. These catalysts also indirectly encourage the removal of sulfur from sterically hindered compounds by eliminating one or both of the aromatic rings contained in dibenzothiophene. Without one or both of the rings, the molecule is much more flexible and the sulfur atom can approach the catalyst surface much more easily. Thus, the desulfurization rate of sterically hindered compounds is greatly increased through the hydrogenation route. The most commonly used hydrogenation/desulfurization catalyst consists of a mixture of nickel and molybdenum (Ni/Mo).

There are a number important issues which should be highlighted about using the hydrogenation pathway for desulfurization. As pointed out above, one or both of the aromatics rings are being saturated which significantly increases the consumption of hydrogen. It is important that one of the aromatic rings of a polyaromatic compound is saturated, as this is the facilitating step which results in the desulfurization of a sterically hindered compound. If the mono aromatics compounds are also saturated, there would likely be a further improvement in the desulfurization reaction rate of the sterically hindered compounds, however at a large hydrogen cost. In addition, certain diesel fuel qualities, such as cetane, would improve significantly as more of the aromatic compounds are saturated. However, the vendors of diesel desulfurization technology explained to us that if cetane improvement is not a goal, then the most cost effective path to desulfurize the sterically hindered compounds is to saturate the polyaromatic compounds to monoaromatic compounds, but not to saturate the monoaromatic compounds. The vendors tell us that because the existence of the monoaromatic compounds is at equilibrium conditions within the reactor, that the monoaromatic compounds are being both saturated and unsaturated, which helps to enable the desulfurization of these compounds.

The vendors also point out a number of reasons why the cycle length of the catalysts which catalyze hydrogenation reactions, which would likely occur in a second stage, is actually longer than the first stage desulfurization catalyst. First, the temperature at which the hydrogenation reactions occur to saturate the polyaromatic compounds to monoaromatic

compounds, but not to saturate the monaromatic compounds is significantly lower than the higher temperatures of the first stage. The lower temperature avoids color changes problems and reduces the amount of coke formation on the hydrogenation catalyst. Furthermore, since the first stage has somewhat “cleaned” the diesel fuel of contaminants such as sulfur, nitrogen and metals, the catalyst in this hydrogenation seconds stage is not degraded as quickly.

If refiners are “upgrading” their diesel fuel by converting heavy, high aromatic, low cetane, stocks to highway diesel fuel under the 15 ppm highway diesel fuel sulfur standard, they are intentionally reacting a lot of hydrogen with the diesel fuel. The hydrogen reactions with the diesel fuel saturates many or most of the aromatics, increases cetane number and reduces sulfur. The lower concentration of aromatics and improved cetane of the upgraded feedstock would then allow the product to be sold as highway diesel fuel. The much higher sales price of the highway diesel fuel compared to the lower value of the feedstock justifies the much larger consumption in hydrogen and the cost of a larger reactor.

Up to a certain level of sulfur removal, the CoMo catalyst is generally preferred. It is more active with respect to desulfurizing non-sterically hindered compounds, which comprise the bulk of the sulfur in distillate, straight run or cracked. Below that level, the need to desulfurize sterically hindered compounds leads to greater interest in NiMo catalysts. Acreon Catalysts had indicated that NiMo are preferred for deep desulfurization around 15 ppm due to this catalyst’s ability to saturate aromatic rings and make the sulfur atom more accessible to the catalyst. On the other hand, Haldor-Topsoe has performed studies which indicate that CoMo catalysts may still have an advantage over NiMo catalysts, even at sulfur levels below 50 ppm.¹⁸

Two-stage processes may also be preferable to achieve ultra-low sulfur levels. Both stages could emphasize desulfurization or desulfurization could be emphasized in the first stage and hydrogenation/desulfurization emphasized in the second stage. In addition to this advantage, the main advantage of two stages lies in the removal of hydrogen sulfide from the gas phase after the first stage. Hydrogen sulfide strongly inhibits desulfurization reactions, as will be discussed further in the next section. It can also recombine with non-sulfur containing hydrocarbon compounds at the end of the reactor or even in subsequent piping, essentially adding sulfur to the desulfurized distillate. Removing hydrogen sulfide after the first stage reduces the hydrogen sulfide concentration at the end of the second stage by roughly two orders of magnitude, dramatically reducing both inhibition and recombination.

In one study, Haldor-Topsoe analyzed a specific desulfurized 50/50 blend of SRGO and LCO at 150 ppm sulfur and found that essentially all of the sulfur is contained in sterically hindered compounds.¹⁹ This feed contains more LCO than would be processed in the typical refinery. A refinery processing less LCO would presumably reach the point where the sulfur compounds were dominated by sterically hindered compounds at a lower sulfur level. They also compared the performance of CoMo and NiMo catalysts on a SRLGO feed at the same space

velocity. The NiMo catalyst performed more poorly than the CoMo catalyst above 200 ppm sulfur, and better below that level. This implies that much of the sulfur left at 200 ppm (and even above this level) was sterically hindered. These two studies indicate that the amount of sterically hindered compounds can exceed the 15 ppm sulfur cap by a substantial margin.

In addition to NiMo catalysts, precious metal catalysts are also very effective in desulfurizing sterically hindered compounds. An example of a precious metal catalyst is the ASAT catalyst developed by United Catalysts and Sud-Chemie AG, which uses both platinum and palladium.²⁰ They are most commonly used to more severely dearomatize distillate and increase cetane by opening up the aromatic rings, a process called ring opening.

b. Meeting a 15 ppm Cap with Distillate Hydrotreating

Using distillate hydrotreating to meet a 15 ppm sulfur cap on highway diesel fuel has been commercially demonstrated, as will be discussed below. Thus, meeting the 15 ppm cap is quite feasible using current refining technology. Assessing the most reliable and economic means of doing so is more complicated. Refiners already hydrotreat their highway diesel fuel to meet a 500 ppm sulfur cap. These hydrotreaters use a variety of catalysts and have a range of excess capacity. Thus, refiners are not all starting from the same place. Many refiners also produce off-highway diesel fuel and heating oil, which have much less stringent sulfur requirements and could, for example, provide a sink for sterically hindered sulfur containing compounds. Finally, the amount of cracked stocks that a refiner processes into diesel fuel varies widely. Those with a greater fraction of LCO will face a more difficult task of complying with a 15 ppm cap, than those processing primarily SRLGO.

To understand the types of modifications which can be made to distillate hydrotreaters in order to improve their performance, it is useful to better understand the quantitative relationships between the various physical and chemical parameters involved in hydrotreating. Haldor-Topsoe has developed the following algebraic expression to describe the rate of desulfurization via both direct desulfurization and hydrogenation/desulfurization.

$$\begin{array}{l} \text{Rate of} \\ \text{Desulfurization} \\ \text{Per Catalyst} \\ \text{Surface Area} \end{array} = \frac{k * C_s^n * P_{H_2}^a}{(1 + K_{H_2S} * P_{H_2S})} + \frac{k * C_s^m * P_{H_2}^b}{(1 + K_F * C_F)}$$

where: k , K_{H_2S} and K_F are various rate constants, which only vary with temperature
 C_s is the concentration of sulfur in the distillate
 P_{H_2} and P_{H_2S} are the partial pressures of hydrogen and hydrogen sulfide in the vapor phase
 $K_F * C_F$ is the total inhibition due to hydrogen sulfide, ammonia, and aromatics
 n , m , a , and b are various constant exponents

The first term represents the rate of direct desulfurization, such as that catalyzed by CoMo. This reaction rate increased by increasing the partial pressure of hydrogen. However, it is inhibited by increasing concentrations of hydrogen sulfide, which competes with the distillate for sites on the catalyst surface.

The second term represents the rate of desulfurization via hydrogenation of the aromatic ring next to the sulfur atom. This rate of desulfurization also increases with higher hydrogen partial pressure. However, this reaction is inhibited by hydrogen sulfide, ammonia, and aromatics. This inhibition by aromatics leads to the presence of a thermodynamic equilibrium condition which can prevent the complete saturation of aromatics. Also, this inhibition makes it more difficult to desulfurize cracked stocks, which contain high concentrations of both sterically hindered sulfur compounds and aromatics. While the literature generally expresses a preference for NiMo catalysts for desulfurizing cracked stocks, Haldor-Topsoe has found situations where this aromatics inhibition leads them to favor CoMo catalysts even for desulfurizing feeds with a high concentration of sterically hindered compounds.

These relationships essentially identify the types of changes which could be made to improve the performance of current distillate hydrotreaters. First, a more active catalyst can be used. This increases the “ k ” terms in the above equations. Second, temperature can be increased, which also increases the “ k ” terms in the above equations. Third, improvements can often be made in vapor-liquid contact, which effectively increases the surface area of the catalyst. Fourth, hydrogen purity can be increased. This increases the P_{H_2} term in the two numerator terms of the equation. Fifth, the concentration of hydrogen sulfide in the recycle stream can be removed by scrubbing. This decreases the P_{H_2S} and C_F terms in the two denominator terms of the equation. Finally, more volume of catalyst can be used, which increases the surface area proportionally.

Regarding catalysts, at least two firms have announced the development of improved catalysts since the time that most distillate hydrotreaters were built in the U.S. to meet the 1993 500 ppm sulfur cap: Akzo Nobel / Nippon Ketjen Catalysts (Akzo Nobel) and Haldor-Topsoe. Akzo Nobel currently markets four CoMo desulfurization catalysts: KF 752, KF 756 and KF 757 which have been available for several years, and KF 848, which was announced this year.²¹ KF 752 can be considered to be typical of an Akzo Nobel catalyst of the 1992-93 timeframe, while KF 756 and 757 catalysts represent improvements. Akzo Nobel estimates that under typical

conditions (e.g., 500 ppm sulfur), KF 756 is 25 percent more active than KF 752, while KF 757 is more than 50 percent more active than KF 752 and 30 percent more active than KF 756.²² However, under more severe conditions (e.g., <50 ppm sulfur), KF 757 is 35-75 percent more active than KF 756. KF 848 is 15 - 50 percent more active than KF 757. Commercial experience exists for both advanced catalysts. KF 756 is widely used in Europe (20 percent of all distillate hydrotreaters operating on January 1, 1998), while KF 757 has been used in at least three hydrotreaters commercially. KF 757 and KF 842 utilizes what Akzo Nobel calls STARS technology, Super Type II Active Reaction Sites. Type II refers to a specific kind of catalyst site which is particular good at removing sulfur from sterically hindered compounds.

In terms of sulfur removal, Akzo Nobel projects that a desulfurization unit producing 500 ppm sulfur with KF 752, would produce 405, 270 and 160ppm sulfur with KF 756, KF757, and KF 842, respectively.

Haldor-Topsoe has also developed a more active catalyst. Its TK-554 catalyst is analogous to Akzo Nobel's KF 756 catalyst, while its newer, more active catalyst is termed TK-574. For example, in pilot plant studies, under conditions where TK-554 produces 400 ppm sulfur in SRLGO, TK 574 will produce 280 ppm. Under more severe conditions, TK-554 will produce 60 ppm, while TK 574 will produce 30 ppm. Similar benefits are found with a mixture of straight run and cracked stocks.

UOP projects a similar reduction in sulfur due to improved catalyst. They estimate that a hydrotreater producing 500 ppm sulfur distillate today (20% LCO, 10% light coker gas oil) could produce 280 ppm sulfur distillate with a 50 percent more active catalyst.²³

Over the last two years, Criterion Catalyst Company announced two new lines of catalysts. One is called Century, and the other is called Centinel.²⁴ These two lines of catalysts are reported to be 45 - 70 percent and 80 percent more active, respectively, at desulfurizing petroleum fuel than conventional catalysts used in the mid-90s. These improvements have come about through better dispersion of the active metal on the catalyst substrate.

Thus, by itself, changing to a more active catalyst can reduce sulfur moderately. Based on the history of the industry, improvements in catalyst performance can be anticipated over time to result in roughly a 25 percent increase in catalyst activity every 4 years. Vendors have informed EPA that the cost of these advanced catalysts is very modest relative to less active catalysts. This will help to reduce the reactor size needed, but by itself would not appear to be sufficient for most refiners to meet a 15 ppm

The second type of improvement is to reduce the concentration of hydrogen sulfide, which reduces the inhibition of the desulfurization and hydrogenation reactions. Hydrogen sulfide can be removed by chemical scrubbing. Haldor-Topsoe indicates that decreasing the

concentration of hydrogen sulfide at the inlet to a co-current reactor by three to six volume percent can decrease the average temperature needed to achieve a specific sulfur reduction by 15-20°C, or reduce final sulfur levels by more than two-thirds. UOP projects that scrubbing hydrogen sulfide from recycle hydrogen can reduce sulfur levels from roughly 285 to 180 ppm in an existing hydrotreater.

The third type of improvement which can be made to current distillate hydrotreaters is to improve vapor-liquid contact. Akzo Nobel estimates that an improved vapor-liquid distributor can reduce the temperature necessary to meet a 50 ppm sulfur level by 10 °C, which in turn would increase catalyst life and allow an increase in cycle length from 10 to 18 months. Based on the above data from Haldor-Topsoe, if temperature were maintained, the final sulfur level could be reduced by 50 percent. Similarly, in testing of an improved vapor-liquid distributor in commercial use, Haldor-Topsoe found that the new distributor allowed a 30 percent higher sulfur feed to be processed at 25°C lower temperatures, while reducing the sulfur content of the product from 500 to 350 ppm. Maintaining temperature should have allowed an additional reduction in sulfur of more than two-thirds. Thus, ensuring adequate vapor-liquid contact can have a major impact on final sulfur levels.

The fourth improvement possible is to increase hydrogen partial pressure and/or purity. As discussed above, this increases the rate of both desulfurization and hydrogenation reactions. Haldor-Topsoe indicates that increasing hydrogen purity is preferable to a simple increase in the pressure of the hydrogen feed gas, since the latter will also increase the partial pressure of hydrogen sulfide later in the process, which inhibits both beneficial reactions. Haldor-Topsoe projects that an increase in hydrogen purity of 30 percent would lower the temperature needed to achieve the same sulfur removal rate by eight to nine °C. Or temperature could be maintained while increasing the amount of sulfur removed by roughly 40 percent. Hydrogen purity can be increased through the use of a membrane separation system or a PSA unit. UOP project that purifying hydrogen can reduce distillate sulfur from 180 to 140 ppm from an existing hydrotreater.

The fifth type of improvement is to increase reactor temperature. Haldor-Topsoe has shown that an increase of 14°C while processing a mix of SRLGO and LCO with its advanced TK-574 CoMo catalyst will reduce sulfur from 120 ppm to 40 ppm.²⁵ UOP projects that a 20 °F increase in reactor temperature would decrease sulfur from 140 to 120 ppm. The downside of increased temperature is reduced catalyst life (i.e., the need to change catalyst more frequently). This increases the cost of catalyst, as well as affects highway diesel fuel production while the unit is down for the catalyst change. Still, current catalyst life currently ranges from six to 60 months, so some refiners could increase temperature and still remain well within the range of current industry performance. The relationship between temperature and life of a catalyst is a primary criterion affecting its marketability. Thus, catalyst suppliers generally do not publish these figures.

Sixth, additional sulfur can be removed by increasing the amount of recycle gas sent to the inlet of the reactor. However, the effect is relatively small. Haldor-Topsoe indicates that a 50 percent increase in the ratio of total gas/liquid ratio only decreases the necessary reactor temperature by six to eight °C. Or, temperature can be maintained and the final sulfur level reduced by 35-45 percent.

Seventh, reactor volume can be increased. UOP projects that doubling reactor volume would reduce sulfur from 120 to 30 ppm.

These individual improvements described cannot be simply combined, either additively or multiplicatively. As mentioned earlier, each existing distillate hydrotreater is unique in its combination of design, catalyst, feedstock, and operating conditions. While the improvements described above are probably indicative of improvements which can be made in many cases, it is not likely that all of the improvements mentioned are applicable to any one unit; the degree of improvement could either be greater than, or less than the benefits that are indicated.

Therefore, many refiners may have to implement one additional technical change listed by UOP to be able to meet the 15 ppm cap standard. This last technical change is to install a complete second stage to the existing, one-stage hydrotreater. This second stage would consist of a second reactor, and a high pressure, hydrogen sulfide scrubber between the first and second reactor. The compressor would also be upgraded to allow a higher pressure to be used in the new second reactor. Assuming use of the most active catalysts available in both reactors, UOP projects that converting from a one-stage to a two-stage hydrotreater could produce 5 ppm sulfur relative to a current level of 500 ppm today.

In addition to these major technological options, refiners may have to debottleneck or add other more minor units to support the new desulfurization unit. These units could include hydrogen plants, sulfur recovery plants, amine plants and sour water scrubbing facilities. All of these units are already operating in refineries but may have to be expanded or enlarged.

Overall, Akzo-Nobel projects that current hydrotreaters can be modified short of a revamp to achieve 50 ppm sulfur. Acreon/IFP/Procatalyse is less optimistic, believing that more than a catalyst change will be necessary to meet this sulfur level.²⁶ BP-Amoco projects that a 70 percent improvement in catalyst activity could reduce sulfur from a current hydrotreater meeting a 500 ppm sulfur specification to 30 ppm.²⁷ While this improvement is somewhat greater than the 50 percent improvement measured by Akzo Nobel at current desulfurization severity, it indicates that it may be possible to improve current hydrotreaters to produce distillate sulfur levels in the 50-100 ppm range. Thus, it appears that additional reductions needed to meet a 15 ppm cap would require additional measures. To assess the degree that these measures would be needed, it is useful to examine the commercial and pilot plant performance of distillate hydrotreaters to achieve very low sulfur levels.

After reviewing the technology for desulfurizing diesel fuel, and discussing the advancements in catalyst technology, it is appropriate to turn to how refiners will invest to meet the 15 ppm cap standard. Refiners have a choice of continuing to use their existing distillate hydrotreater, or to not use that equipment and design an entirely new hydrotreater. As will be shown below, numerous commercial examples exist where existing hydrotreaters have been modified to improve their sulfur removal performance. The vendors of desulfurization technology assert that refiners can meet the 15 ppm cap standard by revamping their existing diesel hydrotreating units. However, several refiners we spoke to indicated that they foresee replacing one or more of their existing diesel hydrotreaters with a brand new “grassroots” unit. One refiner stated that they plan to use the idled units in other places in the refinery.

We gathered more information on whether refiners would revamp versus install a grassroots unit during a session on diesel hydrotreating at this year’s NPRA Q & A conference. The refiners on the panel and in the audience were asked if they would scrap their existing diesel hydrotreaters to install a new grassroots unit if they were faced with the proposed EPA highway diesel standard. The response by one of the refiners was that refiners would not waste good capital units in the refinery, suggesting that the refiners would revamp their existing diesel hydrotreaters with additional capital. However the refiner went on say that some refiners may choose to convert their existing diesel hydrotreaters to gasoline hydrotreaters, or to processing nonroad diesel fuel, once any nonroad requirements are known, and then put in a grassroots unit for diesel hydrotreating. That responder supposed that a refiner might choose to scrap a unit if it “was very, very old,” however, when considering the tone of the commenter’s remarks, he implied that few refiners would indeed scrap their existing highway diesel hydrotreaters. Another refiner said that they currently are not producing as much highway diesel fuel as they would like and that they might build a grassroots unit which would allow them to expand their highway diesel production.

Charles River and Baker and O’Brien, in a study of the cost of desulfurizing diesel fuel for API, also considered the issue of revamps versus grassroots units.²⁸ The API contractors used a set of assumptions to estimate how many of the desulfurization units that would be built to meet a 15 ppm cap standard would be revamped units versus brand new grassroots units. An important assumption of their analysis is that to meet a 15 ppm cap standard, both the first and second stages of diesel desulfurization require moderate to high pressure (800 psi or higher) if LCO is present in the feed to be treated. They also assume that all diesel desulfurization units installed in 1993 to meet the 500 ppm highway diesel sulfur standard are capable of this pressure, while the units which were converted over from another service are not. Finally, the study assumes that a refinery with a hydrocracker is processing its LCO in the hydrocracker and not processing it in the diesel hydrotreater. Based on these assumptions, the study assumed a refiner would revamp a diesel desulfurization unit installed in 1993, and would revamp an older unit if the refinery had a hydrocracker. By deduction, the study assumed that the refineries which had

converted an existing hydrotreating unit to diesel desulfurization service in 1993 but did not have a hydrocracker, would not revamp and put in a grassroots unit. According to API's contractors, this set of assumptions would result in about 60 percent of the refineries revamping their existing desulfurization units and 40 percent of the refineries putting in new grassroots units. The contractors did not include the information which served as the basis for their assumptions about revamps versus grassroots in their final report, and when we asked API for the information, they would not share it with us.

A cost study was conducted by the National Petroleum Council in response to a request from the Department of Energy to study the cost of desulfurizing diesel fuel.²⁹ This study estimated the cost to desulfurize diesel fuel down to an average of 30 ppm. An assumption of the cost study was that current diesel hydrotreaters producing 50 percent of the highway diesel fuel would be retrofitted to meet a 30 ppm sulfur standard, while the other diesel hydrotreaters producing 50 percent of highway diesel fuel would be replaced by new grassroots units. Despite that this study analyzed a much less severe diesel sulfur standard, the study assumed that the industry would have to resort to more grassroots units than the API study.

We project that some refiners will put in new grassroots units. We believe that those refiners that put in grassroots units will do so because they can most economically meet the combination of the Tier 2 gasoline sulfur standard and this highway diesel sulfur standard by converting their existing diesel desulfurization unit to meet the gasoline sulfur requirement. Or, in a few cases, refiners will put in grassroots units because the unit is too old to operate reliably enough to produce diesel on a regular basis which meets the 15 ppm cap standard. However, when we compare the assumptions made in the API and NPC studies to our discussions with refiners and with the comments made by refiners at the NPRA Q & A meeting, we believe that the API and NPC assumptions are too conservative. Regardless of the operating pressure of their existing diesel desulfurization unit, refiners are able to desulfurize distillate down to under 500 ppm to meet the existing highway diesel sulfur standard, a sulfur reduction on the order of 95 percent. In meeting a 15 ppm cap standard, this existing sulfur reduction would provide an important first stage reduction for meeting a 15 ppm sulfur cap standard. We also believe that refiners would not have much to gain by replacing this first stage with a higher pressure first stage. After considering the comments made by the refiners at the NPRA Q & A meeting, the comments made by vendors, and considering that there are few compelling reasons for going with a grassroots unit, we project that the percentage of refiners putting in grassroots units will be between 10 to 30 percent. For our cost analysis we used the average of this range, which is 20 percent.

c. Low Sulfur Performance of Distillate Hydrotreating

Data from both pilot plant studies and commercial performance are available which indicate the capability of various hydrotreating technologies to reduce distillate sulfur levels to

very low levels. While many studies are available which focus on reducing sulfur to 500 ppm or below, studies of achieving lower sulfur levels (e.g., 10-50 ppm) also focus on reducing aromatics content significantly. This combination is related to the fact that Swedish Class II diesel fuel must meet a tight aromatics specification in 2005 along with a 10 ppm sulfur cap.

Reducing aromatic content along with sulfur content is generally desirable with respect to diesel fuel quality, as aromatic reductions increase cetane levels and generally improve combustion characteristics. However, reducing aromatics consumes hydrogen and increases the cost of desulfurization relative to a case where only sulfur was being removed. A number of catalyst and engineering firms have projected the technology necessary to just reduce sulfur without a mandated aromatics reduction (and its cost) for EPA, the Engine Manufacturers Association, the American Petroleum Institute, the National Petroleum Council and others. These projections will be discussed in the next chapter on the economic impacts of this rule. The discussion in this chapter will focus on the available pilot plant and commercial data demonstrating the achievement of low sulfur levels. It is worth noting that until the recent announcements by the German government to seek sulfur levels as low as 10 ppm, there had been little effort by industry to develop technology capable of such a level across the diesel pool. Recent advancements by catalyst manufacturers demonstrating the feasibility of producing diesel fuel which meets these levels through pilot plant testing should be considered a first-generation of technology, with new and continual advancements expected over time.

Starting with SynTechnology, as of August 2, 1999, there were 24 units either in operation or in the process of being constructed. Their purposes range from desulfurization to desulfurization plus dearomatization to mild hydrocracking. Of particular interest here is a revamp of an existing two reactor distillate hydrotreater at the Lyondell / Citgo refinery in Texas.

The revamped unit was designed to process a low-cost feed very heavily weighted towards cracked material (65-70 percent LCO and LCGO). One existing reactor was converted to SynSat Technology, while the other was used simply as a flash drum. A new first-stage reactor was added. Both reactors were designed to operate in a co-current fashion. Pilot plant studies predicted average sulfur and aromatics levels of seven ppm and 31 volume percent, respectively, based on feed sulfur and aromatics levels of 11,900 ppm and 53 volume percent, respectively. The unit exceeded expectations in the case of sulfur, producing an average sulfur level of less than five ppm from a feed sulfur level of 13,800 ppm. The actual aromatic level achieved was above the target by four volume percent, but the feed aromatic level was five volume percent higher than expected. Thus, the net reduction in aromatic content in terms of volume percent was still higher than found in the pilot plant. ABB Lummus and Criterion indicate that their catalyst technology is sufficiently flexible to focus on the deep desulfurization with or without the significant aromatics reduction seen here. This is reflected in their projection of the technology needed to meet a 15 ppm sulfur cap which is discussed in the next chapter.

While this two-stage unit initially produced less than 5 ppm product, it does not do so consistently. The primary purpose of the unit is to increase cetane so that the product can be blended directly into diesel fuel. The primary sulfur reduction requirement is to protect the noble metal catalyst in the second stage reactor. This generally requires that the product from the first stage be less than 50 ppm. Thus, if the cetane specifications are being met at less severe conditions, there is no incentive to reduce sulfur any further than necessary for catalyst protection. In addition, the unit is seeing a heavier feedstock than designed, and the desulfurization reactor is being operated at a lower temperature than designed to increase the cycle lengths.

IFP, in conjunction with various catalyst manufacturers, offers its Prime D technology for deep desulfurization, aromatics saturation and cetane improvement.³⁰ Using a NiMo catalyst, IFP's Prime D process can produce distillate sulfur levels of 10 ppm from SRLGO and of less than 20 ppm from distillate containing 20-100 percent cracked material using a single stage reactor. With a two-stage process, less than one ppm sulfur can be achieved.

United Catalysts and Sud-Chemie AG have published data on the performance of their ASAT catalyst, which uses platinum and palladium.³¹ The focus of their study was to reduce aromatics to less than 10 volume percent starting with a feed distillate containing up to 500 ppm sulfur and at least 100 ppm nitrogen. Starting with a feed distillate containing 400 ppm sulfur and 127 ppm nitrogen and 42.5 volume percent aromatics, the ASAT catalyst was able to reduce sulfur to eight to nine ppm, essentially eliminate nitrogen and reduce aromatics to two to five volume percent. Hydrogen consumption was 800-971 standard cubic feet per barrel (SCFB).

Akzo Nobel recently presented a summary of the commercial experience of about a years worth of operations of their STARS catalyst for desulfurizing diesel fuel at the BP-Amoco refinery in Grangemouth, UK.³² The original unit was designed to produce 35,000 barrels per day of diesel fuel at 500 ppm treating mostly straight run material, but some LCO was treated as well. Akzo Nobel's newest and best catalyst (KF 757 at that time) was dense-loaded^c into the reactor to produce 45,000 barrels per day diesel fuel at 10 - 20 ppm (to meet the 50 ppm cap standard). From the data, it was clear to see that as the space velocity changed, the sulfur level changed inversely proportional to the change in space velocity. Usually when the space velocity dipped below 1.0, the sulfur level dropped below 10 ppm. At that refinery, however, it was not necessary to maintain the sulfur level below 10 ppm.

These studies indicate the commercial feasibility of producing diesel fuel with 10 ppm or less sulfur. The primary issue remaining is to commercially demonstrate that the 15 ppm cap standard can be met using the desulfurization/hydrogenation method without saturating much of

^c Dense loading is a process of packing a certain volume of catalyst into a smaller space than conventional catalyst loading.

the aromatics in diesel fuel, especially with a feedstock blend which contains a substantial amount of cracked material. The ease or difficulty of accomplishing this depends on the amount of cracked stocks that the refiner blends into diesel fuel and the possibility of shifting some of the sterically hindered compounds to fuels complying with less stringent sulfur standards, such as off-highway diesel fuel and heating oil.

d. Undercutting Cracked Stocks

The primary stumbling block preventing the simple desulfurization of distillate to sulfur levels meeting the 15 ppm cap is the presence of sterically hindered compounds, particularly those with two methyl or ethyl groups blocking the sulfur atom. These compounds are aromatic in nature, and are found in greatest concentration in LCO, which itself is highly aromatic. These compounds can be desulfurized readily if saturated. However, due to the much higher hydrogen cost of doing so, it is better economically if this can be avoided. Because these compounds are inherently large in molecular weight due to their chemical structure, they distill near the high end of the diesel range of distillation temperatures. Thus, it is possible to segregate these compounds from the rest of the cracked stocks via distillation and avoid the need to desulfurize them.

Once separated, this LCO material could be mixed into the refinery streams currently being used to produce off-highway diesel fuel and heating oil. These fuels would still have to meet applicable quality specifications, such as cetane, density, sulfur and distillation. For example, the industry specification for non-road diesel fuel is a minimum of 40 cetane number, and a maximum sulfur concentration of 5,000 ppm.³³ An analysis of off-highway diesel fuel shows that off-highway diesel fuel averages 44.4 cetane number, 3,300 ppm sulfur, 34.5 API gravity, T10 of 438 °F, T50 of 517 °F, and T90 of 600 °F.³⁴ We anticipate that refiners would need to use cetane additives to compensate for the addition of LCO to maintain off-highway fuel cetane levels similar to those of current in-use fuels (see Section V). Additional cold-flow additives might also be necessary for off-highway diesel fuel in the winter to maintain cold-flow performance at current levels. We anticipate that refiners would allow other off-highway and heating oil properties to change as a result of the addition of LCO, while continuing to ensure that all specifications on these fuels are met.

Shifting LCO to off-highway diesel fuel and heating oil would prevent the need to desulfurize a sizeable fraction of the sterically hindered compounds currently present in highway diesel fuel. For example, Akzo Nobel studies indicate that a drop of 10 °C in the 95th percentile distillation point (T95) of diesel fuel decreases sulfur from 50 - 60 ppm.³⁵ Of course, such a shift to non-highway diesel fuel markets would decrease the amount of highway diesel fuel produced, about 3 percent for the typical refinery, if more easy to hydrotreat material was not switched from non-highway diesel fuels to the highway diesel fuel pool. A decrease of T95 of this magnitude effected by undercutting only LCO would decrease sulfur even more because the sulfur levels in the heaviest portions of LCO are much greater than those in SRLGO and are the most difficult to desulfurize. Shifting only heavy LCO would increase the sulfur reduction per

volume of highway diesel fuel lost, but would still result in a net loss of highway diesel fuel production if no other feedstocks replaced it.

While this heavy LCO material could be shifted to other markets, this does not necessarily have to be the case. Under certain conditions, this material can be recycled to the FCC unit.³⁶ For this to be feasible, the refiner must hydrotreat the FCC feed at a pressure sufficient to desulfurize the sterically hindered sulfur containing compounds and the feed hydrotreater must have sufficient excess capacity to handle the additional material. This material could also be sent to an existing hydrocracker, if sufficient capacity existed, and converted into gasoline blendstock. Or, it could be hydrotreated separately under more severe conditions to remove the sulfur, such as with SynAlliance's SynShift process. This would entail higher hydrogen consumption per barrel of treated material because of some aromatic saturation. However, the amount of material being processed would be small, so overall hydrogen consumption would still be low.

A number of vendors of distillate desulfurization processes recently developed specific projections of the technology needed to meet a range of highway diesel fuel sulfur levels. These projections were developed to support refining cost studies conducted by the Engine Manufacturers Association and the American Petroleum Institute, and the National Petroleum Council.^d These projections addressed compliance with three different average sulfur levels: 10, 30 and 100 ppm. Generally, these projections indicate that it will be possible for refiners to meet the 10 ppm average sulfur level without resorting to catalysts and operating conditions which reduce aromatic levels dramatically. Thus, it appears that the cost of providing sufficient hydrogen to saturate these aromatics can be avoided. The specifics of these projections will be addressed in more detail in the next chapter.

6. Other Desulfurization Technologies

a. Biodesulfurization

Biodesulfurization is essentially an alternative to distillate hydrotreating. This process is being developed by Energy Biosystems. It involves the removal of sulfur-containing hydrocarbon compounds from distillate or naphtha streams using bacteria. The distillate stream is first mixed with an aqueous media containing the bacteria, caustic soda and nutrients for the bacteria. Enzymes in the bacteria first oxidize the sulfur atoms and then cleaves some of the sulfur-carbon bonds. The sulfur leaves the process in the form of hydroxyphenyl benzene sulfonate, which can be used commercially as a feedstock to produce surfactants. Designs based on pilot plant studies combine biodesulfurization with conventional hydrotreating to produce diesel fuel containing 50 ppm sulfur.

^d See Chapter V for additional discussion on these projections.

b. Chemical Oxidation and Extraction

Another desulfurization technology was announced by Petrostar this year which desulfurizes diesel fuel using chemical oxidation.³⁷ Desulfurization of diesel fuel is accomplished by first forming a water emulsion with the diesel fuel. In the emulsion, the sulfur atom is oxidized to a sulfone using catalyzed peroxyacetic acid. With an oxygen atom attached to the sulfur atom, the sulfur-containing hydrocarbon molecules becomes polar and hydrophilic and then move into the aqueous phase. Like biodesulfurization, some of the sulfones can be converted to a surfactant which could be sold to the soap industry at an economically desirable price. The earnings made from the sales of the surfactant would offset much of the cost of oxidative desulfurization.

We are aware of another chemical oxidation process which currently is in the patenting process. This process is similar to the Petrostar process, except instead of keeping the sulfone intact, this process separates the oxidized sulfur atom from the hydrocarbon immediately after the oxidation reaction. The resulting sulfate is easily separable from the petroleum. While this process does not create a valuable byproduct, it would likely be a less capital intensive means to make the sulfur separation than the Petrostar process.

c. Sulfur Adsorption

A prospective diesel desulfurization process was recently announced by Phillips Petroleum.³⁸ This process is an extension of their S-Zorb process for gasoline. S-Zorb for diesel contacts highway diesel fuel (typically with about 350 ppm sulfur) with a catalyst in a reactor at relatively low pressures and temperature in the presence of hydrogen. The sulfur atom of the sulfur-containing compounds adsorbs onto the catalyst. The catalyst next cleaves the sulfur atom from the sulfur-containing hydrocarbon. To prevent the accumulation of sulfur on the catalyst, the catalyst is continually removed from the reactor. In a separate regeneration vessel, the sulfur is burned off of the catalyst and is sent to the sulfur plant. The regenerated catalyst is then recycled back to the reactor for removing more sulfur. Because the catalyst is continuously being regenerated, the catalyst should never force the unit to be shutdown, thus, Phillips estimates that the unit will be able to operate 4 - 5 years between shutdowns. Because untreated distillate can contain several percent sulfur, Phillips believes that its S-Zorb process for diesel could get overwhelmed by the amount of sulfur which is adsorbing onto the catalyst. Thus, the S-Zorb process may not be able to treat untreated distillate streams, but would likely be used to treat distillate containing 500 ppm sulfur or less.

Phillips' diesel desulfurization process has only been demonstrated in the laboratory up to this point. The laboratory testing has shown that diesel with LCO can be desulfurized down below 5 ppm. However, Phillips is on the fast track to demonstrate this process in a pilot plant and in a commercial unit. First, the company reports that its S-Zorb commercial demonstration unit for gasoline is on schedule to startup the first quarter of 2001. Since the process has never

been demonstrated commercially, this demonstration unit will go a long way toward proving that the Phillips process works as designed. However, the sulfur compounds in diesel fuel are different, usually more refractory, than those in gasoline. Phillips reports, though, that the absorption catalyst more readily desulfurizes the sterically hindered sulfur compounds than the thiophenes (single ring compounds which contain sulfur) which must be desulfurized in gasoline. This suggests the possibility that S-Zorb for diesel may actually desulfurize current highway diesel fuel more easily than S-Zorb for gasoline. Phillips projects that they will have an S-Zorb diesel desulfurization pilot plant up and running by the third quarter of 2001, and a commercial unit up and running during the fourth quarter of 2003. After hearing Phillips' timeline for developing the S-Zorb diesel desulfurization process, and weighing the uncertainty associated with S-Zorb, it seems that refiners may consider this process too risky for 2006. However, this process could be far enough along in its development to be used by refiners in 2010.

d. FCC Feed Hydrotreating

At the beginning of Section 3., it was mentioned that sulfur could be removed from distillate material early or late in the refining process. Early in the process, the most practical place to remove sulfur early in the process is prior to the FCC unit. The FCC unit primarily produces gasoline, but it also produces a significant quantity of distillate, called LCO as described in Section A.1 above. LCO is high in aromatics and sulfur and contains a relatively high fraction of the sterically hindered sulfur compounds found in diesel fuel.

Many refineries already have an FCC feed hydrotreating unit. The LCO from these refineries should contain a much lower concentration of sterically hindered compounds than refineries not hydrotreating their FCC feed. Adding an FCC feed hydrotreating is much more costly than distillate hydrotreating. Just on the basis of sulfur removal, FCC feed hydrotreating is more costly than distillate hydrotreating, even considering the need to reduce gasoline sulfur concentrations, as well. This is partly due to the fact that FCC feed hydrotreating by itself is generally not capable of reducing the level of diesel fuel sulfur to those being considered in this rule. However, FCC feed hydrotreating provides other environmental and economic benefits. FCC feed hydrotreating decreases the sulfur content of gasoline significantly, as well as reducing sulfur oxide emissions from the FCC unit. Economically, it increases the yield of relatively high value gasoline and LPG from the FCC unit and reduces the formation of coke on the FCC catalyst. For individual refiners, these additional benefits may offset enough of the cost of FCC hydrotreating to make it a more economical than distillate hydrotreating. However, these benefits are difficult to estimate in a nationwide study such as this. Thus, this study will rely on distillate hydrotreating as the primary means with which refiners would meet the 15 ppm sulfur cap. For those refiners who would choose FCC feed hydrotreating, their costs would be presumably lower than distillate hydrotreating and the costs estimated in the next chapter can then be considered to be somewhat conservative in this respect.

7. Will There Be Enough Supply of Highway Diesel Fuel?

First, in assessing the cost of desulfurizing highway diesel fuel, we began with the assumption that sufficient desulfurization equipment would have to be constructed to adequately supply diesel highway vehicles, as well as other users of highway diesel fuel. We examined historic production and demand of highway diesel fuel, factored in growth per estimates by EIA, and determined that amount of highway diesel fuel which would have to meet the 15 ppm cap both during and after the initial period during which the temporary compliance option and various hardship provisions are in effect.

The issue of future supply of highway diesel fuel was raised in the NPRM and received considerable attention during the comment period. Numerous commenters to the proposed rule indicated that they believed that the 15 ppm sulfur cap would cause shortages in highway diesel fuel supply. A number of commenters also thought otherwise (i.e., that future supplies would be adequate). These comments are summarized in Section 8.1.1 of the Response to Comments document for this rule. The factors which affect refiners' decisions on how much 15 ppm diesel fuel to produce fall into the following categories:

- Required investment per refinery
- Historic refining profit margins
- Variation in compliance costs between refiners
- Other markets for highway diesel fuel
- Uncertainty in requisite desulfurization control technology
- Likely price and import response to new sulfur standard
- Impact of desulfurization processes on fuel volume, and
- Impact of fuel transport on fuel supply

Each of these factors is addressed below. In addition, the findings of a study performed by Charles River Associates and Baker and O'Brien for API concerning the potential supply impacts of the new sulfur standard are discussed at the end of this section.

a. Required Investment per Refinery

The first issue is that the level of investment per refinery required to meet this diesel sulfur standard is more than that required to meet the recent Tier 2 gasoline sulfur standard. This is true. We projected that it would cost \$44 million per refinery to meet the Tier 2 gasoline sulfur standards, while we project that it will cost \$50 million per refinery to meet the diesel fuel sulfur cap. In addition, this \$50 million figure represents the average of revamped units (which will cost less) and new units (which will cost more). Revamping an existing diesel hydrotreater (representing roughly 80 percent of all current units) will cost roughly \$40 million, while a new diesel hydrotreater will cost \$80 million. Thus, roughly 25 refineries will face twice the

investment cost to meet this diesel standard as they did to meet the Tier 2 gasoline sulfur standards.

This difference in investment is to be expected. Nearly all of the sulfur in gasoline is contained in the naphtha (material boiling in the gasoline boiling range) produced in the fluidized catalytic cracker (FCC). Generally, this is the only material which needs to be hydrotreated in order to meet the 30 ppm average sulfur standard. In contrast, all diesel blendstocks, except for that from a hydrocracker (4 percent of all blendstocks) will need to be hydrotreated in order to meet the 15 ppm cap. Refiners produce roughly the same volumes of FCC naphtha and highway diesel fuel. However, diesel fuel desulfurization requires much higher temperatures and pressures, and the material must be in contact with the catalyst for longer periods of time, so the capital investment per unit volume of treated material is much higher. Finally, because refineries make 3-4 times as much gasoline as highway diesel fuel, the investment per gallon of finished fuel is 3-4 times higher for diesel fuel.

This higher investment per unit volume of product means that refiners will be putting more investment at risk relative to potential profit in the case of diesel fuel than gasoline. As will be discussed further below, the market sometimes allows refiners to recoup their full cost of meeting environmental standards (operating plus capital costs) and sometimes only allows them to recoup operating costs. The greater level of investment per unit volume of product means that refiners would have to cover 3-4 times the investment cost per gallon of fuel if the market does not reward them with a price increase which allows the recovery of capital plus a reasonable return on this investment. Directionally, this means that refiners will look much more closely at the market situation for diesel fuel before making the investment to meet the 15 ppm standard. In particular, refiners are likely to carefully assess their competitors' actions to ensure that significant overcapacity does not exist, which decreases refining margins.

The second issue is that, of late, relatively poor refining margins have not allowed refiners to recoup the full cost of environmental standards. Two examples are the 500 ppm sulfur diesel fuel standard and the RFG standards. In both cases, over-investment by the refining industry led to over-supply of these fuels and low prices.

b. Historic Refining Profit Margins

Over the past year, refining margins have improved dramatically. Domestic refineries are operating at full practical capacity and are expected to do so for the foreseeable future. Thus, the market may have begun a long term period where refining margins will be strong and reward refiners who invest in additional capacity. Refiners also know that even slight shortages in highway diesel fuel supply would lead to significant price increases and substantial profits for those in the market. Thus, as always there will be a tension between wanting to invest and reap the rewards of a potentially short market and the concern over over-investment and the inability to recover investment. The large investment per unit volume of product will make this a more

difficult situation to balance than in past regulatory requirements. However, the temporary compliance option will help counter this difficulty, as it will allow many refineries currently producing highway diesel fuel to delay their investment until 2010. Thus, refiners who are in a better financial position to take the financial risk involved in such a significant investment can do so, while those which are not in as good a position can wait until 2010, buying credits in the meantime.

c. Variation in Compliance Costs Faced by Refiners

The third issue related to supply is the range of costs faced by refiners in complying with the diesel sulfur standard. Our refinery by refinery analysis indicates that refineries face a wide range of compliance costs. If each refinery currently producing highway diesel fuel invests to just maintain their current production, costs range from under 3 cents per gallon to under 12 cents per gallon. It is probably unreasonable for a refiner to expect the market to allow a long term increase in the price of diesel fuel of 12 cents per gallon.^e However, our refinery model also indicates that some refineries can produce 15 ppm diesel fuel from their current nonroad diesel fuel blendstocks more cheaply than many refineries which currently produce highway diesel fuel.

In assessing where the additional volume of nonroad diesel fuel blendstocks would come from, we considered both refineries which produce both highway and nonroad diesel fuel today, as well as refineries which only produce nonroad diesel fuel. Based on the volume and characteristics of each refinery's nonroad diesel blendstocks, we projected which refineries could increase production of highway diesel fuel most economically. We found that many refineries could increase production of highway diesel fuel from blendstocks currently used to produce nonroad diesel fuel as or more economically than many refineries currently producing highway diesel fuel. Thus, there appears to be a plentitude of distillate blendstocks available from which to produce highway diesel fuel.

In addition to requiring that these nonroad diesel fuel blendstocks be processed to compensate for the loss of highway diesel fuel during production and distribution, we also allowed highway diesel fuel produced from these nonroad diesel fuel blendstocks to supplant highway diesel fuel produced at refineries facing higher desulfurization costs. The following table presents the maximum cost in each PADD before and after this adjustment. It should be noted that shifts of fuel production across PADDs were very limited. No transfers were allowed into or out of PADDs 4 and 5. PADD 3 was allowed to increase fuel shipments to PADD 1 and to the southern portion of PADD 2. No shifts were allowed between PADDs 1 and 2.

^e A few small refiners are among those facing higher compliance costs. Many of these refiners are expected to take advantage of EPA's option to delay their compliance with the Tier 2 gasoline sulfur standards. This delay in their gasoline related investment and operating costs will allow these refiners to recoup their diesel fuel-related investment with a much lower price increase than would otherwise be the case.

Table IV.A-7. Maximum Cost of Meeting the 15 ppm Cap (cents per gallon) ^A					
	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5 ^B</i>
All Current Highway Diesel Fuel Producers Continue to Produce					
2006-2010	4.8	4.6	4.2	5.5	4.3
2010 and beyond	9.6	9.7	11.9	9.1	8.9
With Minor Shifts in Production Between Highway and Nonroad Diesel Fuel					
2006-2010	4.8	4.6	4.1	5.5	4.3
2010 and beyond	5.5	7.4	5.1	8.2	5.1

^A Excludes small refiners which we project would chose to produce 100% 15 ppm diesel fuel in 2006 and in return would be granted a three-year extension in meeting the Tier 2 gasoline sulfur standards.^f

^B Excludes Hawaii and Alaska, where maximum costs are 4.8-5.3 cents per gallon.

The difference between the maximum costs during the initial years are nearly identical regardless of whether shifts between highway and nonroad diesel fuel production occur. However, greater differences appear when the entire highway diesel fuel pool must meet the new standard. This occurs because it appears that a very small fraction of current highway diesel fuel production faces very high desulfurization costs, primarily because of extremely low production volumes (i.e., poor economies of scale). By shifting only 1.4 percent of current highway diesel fuel volume to nonroad diesel, the reductions in the maximum costs shown in bottom line of Table V.C-3 occur. Thus, only a very small percentage of current highway diesel fuel production volume faces costs well above the average. Likewise, it appears that ample highway diesel fuel can be produced from nonroad diesel fuel blendstocks at reasonable costs. The costs to produce highway diesel fuel from nonroad diesel fuel blendstocks assume the use of two-stage, conventional hydrotreating. Costs for those refineries not meeting the new standard until 2010 could be much lower if novel, lower cost technologies, such as Phillip’s SZorb process perform as well as expected.

Also discussed in Chapter 5 of this RIA, the temporary compliance option allows a large number of refineries, roughly up to 58, to delay production of 15 ppm diesel fuel until 2010.

^f These refineries were excluded because the three-year delay in meeting the Tier 2 gasoline sulfur standards provides these refineries with economic benefits which can be used to compensate for the cost of meeting the 15 ppm diesel fuel sulfur cap. Thus, the actual cost of meeting the diesel sulfur cap is lower than indicated by our refinery model, which only considers the cost of diesel fuel desulfurization.

(This presumes that the roughly 63 refineries investing in desulfurization equipment in 2010 and producing 100 percent 15 ppm diesel fuel make their credits available to these other refineries.) First, these 58 refineries will be able to observe the performance of the various technologies selected by the other 63 refineries for almost 2 years before making final decisions regarding the technology they will utilize. Second, they will be able to observe the reaction of the market to the new fuel, particularly demand for use in older vehicles and to some degree, prices. However, prices during the initial years will likely differ from those once the program is fully implemented. This brings us to the third benefit of the temporary compliance option, small refiner hardship, and GPA provisions.

As indicated in Table IV.A-7, the refineries producing 15 ppm diesel fuel in 2006 should face lower costs than those delaying production until 2010. This difference in compliance cost is primarily due to lower capital-related costs. Since the biggest risk facing a refiner is the possibility that the market price increase after the implementation of the new standard will not allow the recovery of both operating and capital costs, the lower the capital cost, the lower the risk that substantial amounts will not be recovered. Also, the 75 or so refineries will only be able to delay investment until 2010 if they buy credits from those producing more than 70 percent of their highway diesel fuel under the 15 ppm cap. Thus, these 75 refineries will be subsidizing the cost of producing the 15 ppm fuel through the purchase of credits. The net cost of producing both 15 and 500 ppm fuels should be the same. This is illustrated by the following example.

Assume refinery A produces 70,000 bbl/day of highway diesel fuel, all meeting the 15 ppm cap. Also assume that the cost of meeting the new standard is 4 cents per gallon. Refinery B produces 30,000 bbl/day of highway diesel fuel meeting the 500 ppm cap. Its costs do not change from today. Refinery A generates 21,000 bbl/day of credits, while refinery B needs 21,000 bbl/day of credits. The two refiners will negotiate a price for the credits, which will be a function of how many other sources of credits are available. However, if we assume that Refinery A is willing to sell its credits at cost, then Refinery A will sell 21,000 bbl/day of credits at 4 cents per gallon. Since 21,000 bbl/day represents 30 percent of its production, selling these credits reduces Refinery A's average cost to 2.8 cents per gallon. Refinery B, on the other hand, paid 4 cents per gallon for 70 percent of its production. Thus, its average cost is 2.8 cents per gallon; the same as Refinery A's average cost.

This example demonstrates that with credit trading, the refining costs of both 15 and 500 ppm fuels should be roughly the same. This should lead to the two fuels having similar prices at retail where both fuels are sold. In fact, given that 15 ppm will be the dominant fuel being produced and needs to be distributed throughout the U.S., it will likely be transported by pipeline. 500 ppm fuel, on the other hand, need not be distributed everywhere, since all vehicles can burn the 15 ppm fuel. Thus, distribution of 500 ppm fuel may be concentrated around refining areas and along major pipeline corridors. The price of 500 ppm fuel is likely to be slightly lower than that of 15 ppm fuel in these areas to encourage older vehicle owners to buy

500 ppm fuel and minimize the areas to which the 500 ppm fuel must be distributed. Thus, the risk of a large price differential encouraging misfueling should be low.

The temporary compliance option also makes this diesel fuel program more similar to the RFG program wherein not every refiner need participate, at least for the initial years. By the time that refiners need to make their final decisions on whether to construct new equipment in time to meet the new standard by 2010, the desulfurization units built for 2006 will have been operating for at least one year. This will give refiners evaluating compliance for 2010 considerable confidence in both the cost and performance of the technologies which are available. These refiners will also be able to observe the response of the market to the new fuel in terms of price. While we project that the price of 15 ppm fuel will be very similar to the price of 500 ppm fuel at refinery gates, this is due to the credit trading system. We expect that the price of both fuels will increase with the implementation of this rule. Knowledge of the cost and performance of the desulfurization technology and this market response to the new fuel should be particularly helpful to refiners needing to borrow money to fund the new equipment.

d. Other Markets for Highway Diesel Fuel

Current highway diesel fuel easily meets the specifications for nonroad diesel fuel or heating oil. However, the market for these other distillate fuels is not large enough, nor growing fast enough to absorb much highway diesel fuel. Plus, the highway diesel fuel market is currently in balance, so any decrease in domestic supply would have to be made up by imports.

In order to assess the potential for refiners to sell their current highway diesel fuel or some of the blendstocks used to produce highway diesel fuel into alternative markets, EPA contracted with SwRI and Muse, Stancil to assess these other markets. Muse, Stancil found that refiners would have very limited possibilities of disposing of highway diesel fuel or its blendstocks domestically. Only PADD 1 imports significant quantities of nonroad diesel fuel or heating oil. Refineries in PADD 1 could produce more of this fuel and back out imports. However, refineries in other PADDs would have to export any fuel which they back out of the highway diesel fuel market. Based on historical prices (i.e., highway diesel fuel priced under the 500 ppm sulfur standard), Muse, Stancil estimates that refiners outside of PADD 1 would lose 3-6 cents per gallon in revenue if they shift even 5 percent of their highway diesel fuel to the nonroad diesel fuel market. These losses increase to 4-20 cents per gallon if they shift over 5 percent of their current highway diesel fuel to these alternative markets. Refiners in PADDs 2 and 4 would be particularly hard pressed, as they would have to ship their product to the US Gulf Coast prior to exportation. This adds significant transportation costs, as there are no pipelines flowing from PADDs 2 or 4 to the Gulf.

Should refiners shift highway diesel fuel production to these other markets, it will not only affect the price of the shifted product. The price of all nonroad diesel fuel and heating oil will drop. Refiners trying to sell their highway fuel into these other markets will try to sell it

locally prior to exportation. These refiners will compete with those currently producing nonroad diesel fuel and heating oil, depressing prices in the entire market. Despite lower prices, fuel demand will not increase substantially, since the use of nonroad equipment is a very weak function of fuel price. (For example, fuel costs are a small portion of the total cost of farming, mining and construction, so one would not expect that the demand in these sectors of the economy would be very responsive to fuel price.) Thus, refiners planning on shifting their highway fuel to alternative markets will not only have to consider the decrease in market value of the shifted product, but also the drop in value of their existing nonroad fuel and heating oil production. This added cost of a drop in highway diesel fuel production would vary widely from refinery to refinery since some refineries produce much more nonroad diesel fuel than highway fuel and vice versa.

This loss in market price serves as a discouragement to shift highway diesel fuel to these other markets. It basically provides refiners with a second reward for investing in desulfurization equipment in order to stay in the highway diesel fuel market. First, investment allows them to obtain the price rise of highway diesel fuel which should accompany the new sulfur standard to be achieved. Second, investment allows the price drop associated with export to be avoided, as well as reduces the potential for a drop in value in existing nonroad diesel fuel production. (This last factor is a function of other refiners' decisions, as well, in this area.) Thus, a refiner should desire to invest in meeting the new standard if he believes that the price increase in highway diesel fuel will be at least the cost of meeting the standard minus the loss associated with export. For example, if it costs up to 7 cents per gallon to meet the 15 ppm standard, then the required price increase in highway diesel fuel price may only need to be 3 cents per gallon for refineries to prefer meeting the 15 ppm standard versus taking a loss in the nonroad market of 5 cents per gallon (ignoring any price drop for existing nonroad diesel fuel production). The lack of a ready domestic alternative market for their product appears to be a strong discouragement to refiners shifting their production away from highway diesel fuel.

e. Uncertainty in Requisite Desulfurization Technology

The next factor which could affect highway diesel fuel supply is uncertainty in what technology will be required to meet the 15 ppm standard. As discussed in Section 8.1.2 below and in the RIA, uncertainty does exist concerning the requisite desulfurization technology. Most vendors project that two-stage conventional hydrotreating at low to moderate hydrogen pressure will be sufficient to achieve the new standard, even with significant quantities of LCO. Most refiners commenting on the rule, plus 1-2 vendors believe that moderate to high pressures will be needed, accompanied by more aromatic saturation and hydrogen consumption. In addition, Phillips Petroleum just announced that they have developed a new, low pressure process which promises to consume no hydrogen. This process cannot yet be licensed, but Phillips hopes to begin licensing next year. However, a commercial unit utilizing this technology will not start up until 2004.

The uncertainty in current technology which will be necessary to achieve the new standard could encourage some refiners to delay investment until the latest possible time while still allowing time to build their equipment in time for the 2006 implementation date. The promise of lower costs based on refiner's experience meeting the new standard in 2006 or with the new Phillips technology could encourage refiners to delay the construction of new equipment until beyond the 2006 implementation date. In some cases, particularly refiners located in isolated areas where hydrogen costs are high, the promise of lower long term compliance costs in one to two years could be preferable to the lower revenues obtained from selling highway diesel fuel into the nonroad diesel fuel market in the short term.

Countering the benefit of more leadtime with respect to conventional hydrotreating technology is the fact that vendors will have 2-3 years to generate both pilot plant and commercial data to convince refiners of the efficacy of their processes. While no refiners are currently required to meet a 15 ppm cap prior to 2006, numerous two-stage (and low space velocity one-stage) hydrotreating units exist world-wide. Vendors and refiners are likely to utilize these units to demonstrate their catalysts commercially. This is already being done with some units in Europe. Thus, the largest detriment to investing to meet the new standard in 2006 is the potential cost savings associated with novel technologies such as Phillips' SZorb. These technologies are sufficiently different from conventional hydrotreating that refiners are likely to require full-size commercial operation for a year or two prior to betting tens of millions of dollars on their effectiveness. With the temporary compliance option, refiners able to delay investment until 2010 should be able to utilize the newer technologies, such as SZorb.

f. Likely Price and Import Response to the New Standard

Moving onto the likely price increase which will accompany the new standard, it is very difficult to predict whether the future market price of highway diesel fuel will increase enough to cover only operating costs or operating plus capital costs. No one can predict future prices, so the real issue is what refiners project the price increase will be at the time they need to invest in order to meet the new standard. As mentioned above, the 1990's were not good to refiners; refining margins were poor. Refiners generally did not recover their capital investments which were associated with environmental programs.

However, the demand for fuel continues to grow and domestic refinery capacity is growing at only about half the rate of growth in demand. Imports of finished fuel, including highway diesel fuel are increasing. Also, refining margins during the past year have been excellent for most refiners. Integrated oil company profits have also been at record levels. The net income of individual major oil companies over the 2nd and 3rd quarters of 2000 (e.g., ExxonMobil) was sufficient to fund all of the capital investment associated with this rule. If these refining margins continue for any appreciable amount of time, the availability of capital should not be an issue, even considering other environmental programs facing refiners. These include the Tier 2 gasoline sulfur requirements and NESHAP standards for FCC units, reformers

and sulfur plants. We analyze the combined capital investments associated with the gasoline and diesel fuel sulfur programs later in this chapter of the RIA. There, we found that the level of capital investment per year will be lower than that occurring in the early 1990's, when most of the programs associated with the Clean Air Act of 1990 were being implemented and when refining margins were low. Thus, from an industry wide perspective, the availability of capital should not be a problem. The temporary compliance option helps this situation substantially. A few individual refiners could have difficulty raising sufficient capital to meet the new diesel sulfur standard. We have included hardship provisions in this rule to accommodate at least some of these situations. In addition, as discussed above, not every refiner currently producing highway diesel fuel will need to continue to do so in order to meet future demand.

Overseas refiners may not be as able to produce diesel fuel under the new 15 ppm cap, as they have been under the current 500 ppm cap. The three largest exporters of diesel fuel to the U.S. are Canada, the Virgin Islands and Venezuela. The Canadian refineries which export to the U.S. are located in the far eastern portion of Canada and send the vast majority of their production to the U.S. The same is true of the largest Virgin Island refinery, which has U.S. ownership. These refineries look to the U.S. as their main market. Thus, they are as likely to invest to meet the new standard as any domestic refinery. Venezuelan refineries are in a somewhat better position to send their diesel fuel elsewhere and could be less likely than domestic refiners to invest in new desulfurization equipment. At the same time, Europe and Japan are implementing 50 ppm diesel sulfur caps and Europe is already considering a 10 ppm cap. Thus, export oriented refineries world-wide will have to invest to at least meet a 50 ppm cap and will likely prepare for even lower standards. Even a refinery designed to produce 50 ppm sulfur diesel fuel is capable of producing some 15 ppm fuel. This may require reducing volumetric throughput or cutting the endpoint of its most difficult to hydrotreat blendstocks. However, such refineries should be able to send diesel fuel to the U.S. even if they do not design to do so on a regular basis. Several overseas refiners are likely to closely observe the investment patterns of U.S. refineries to assess the economics of exporting their diesel fuel under the new standard.. Thus, overall, exporting fuel to the U.S. will be more difficult under the new standard, but supplies should be available if necessary. Again, the temporary compliance option helps this situation by allowing importers to import three gallons of 500 ppm fuel for every seven gallons of 15 ppm brought into the country.

g. Impact of Desulfurization Processes on Fuel Volume

Conventional desulfurization processes both reduce the physical and energy density of diesel fuel. Desulfurization actually increases the volume of diesel fuel produced, but each gallon of diesel fuel contains less energy. Overall, the total amount of energy leaving the hydrotreater in the form of diesel fuel decreases by roughly 1.5 percent. Vehicular fuel economy is directly proportional to fuel energy density. Thus, in order in to provide the same number of vehicle miles, refineries will need to increase the volume of blendstocks which they process by

1.5 percent. As discussed in Chapter 5, our cost projections consider this loss of diesel fuel volume in assessing the hydrotreating capacity needed by refiners.

In terms of supply, the effect is much less. Most of the energy lost to diesel fuel is in the form of naphtha or LPG. This increases the refinery's production of these products. This allows the refinery to make other adjustments which increase diesel fuel production at the expense of gasoline, bringing the net production of both products back into balance.

h. Impact of Fuel Transport on Supply

The final factor potentially affecting supply is the possibility that 15 ppm diesel fuel produced at a refinery will be contaminated during shipment and becoming unsuitable for use in 2007 and later highway vehicles. As discussed in Chapter 5 of this RIA, we expect refiners to produce diesel fuel with an average of 7 ppm under the new standard. However, some batches are likely to be higher than this. Pipelines are likely to set their own limits below 15 ppm (e.g., 10 ppm). This means that diesel fuel can only pick up 5 ppm sulfur during distribution, given the testing allowance provided in the final rule. As also discussed in Chapter 5, we estimate that current loss of highway diesel fuel to nonroad diesel market of 2.2 percent will double to 4.4 percent. This increases the production requirements for 15 ppm diesel fuel, but not for total diesel fuel, since the volume lost during distribution can be used as nonroad diesel fuel or heating oil.

As was done for the volume lost during hydrotreating, we considered that refineries would have to process 2.2 percent more diesel fuel blendstocks to produce enough highway diesel fuel to account for losses in the distribution system. This additional volume of blendstocks came from blendstocks currently being used to produce nonroad diesel fuel and heating oil.

i. Charles River Associates and Baker and O'Brien Study

The study by Charles River Associates (CRA) and Baker and O'Brien, which was commissioned by API, assessed refiners ability to maintain an adequate supply of highway diesel fuel under the 15 ppm cap. As part of this study, CRA polled refiners concerning their plans under a 15 ppm sulfur cap. Using the results of this survey, as well as other information, CRA projected refiners' costs of meeting the 15 ppm standard, as well as their likely production volumes. CRA concluded that U.S. refiners would likely reduce their highway diesel fuel production by an average of 12 percent, creating significant shortages and price spikes.

CRA's conclusions appear to have been strongly affected by their assumptions, as well as the refiner survey they conducted. For example, CRA assumed that the new sulfur standard would cause 10 percent more highway diesel fuel to be "lost" in the distribution system compared to today (i.e., downgraded to off-highway diesel fuel). We believe based on the

analysis outlined in the RIA that 2.2 percent is a more accurate estimate, resulting in 9 percent more 15 ppm fuel being available than CRA estimated. This difference alone accounts for 75 percent of the potential national supply shortfall projected by CRA.

CRA also concluded, with little explanation, that 20 refineries producing highway diesel fuel today would not produce highway diesel fuel under the 15 ppm standard and that many more would reduce production. Given the lack of information provided in the study, it was not possible to evaluate CRA's criteria in selecting these 20 refineries, nor was it possible to determine how much of the shortfall was attributable to this conclusion. While CRA evaluated whether refiners currently producing highway diesel fuel would be likely to leave the market, they did not assess whether any refineries currently not producing highway diesel fuel might enter the market. EPA did conduct such an assessment. We found 2 refineries that produce essentially no highway diesel fuel today which could meet the new standard for less than 5 cents per gallon. Production from these refineries would increase highway diesel fuel production by 9 percent. We also found based on our assessment that 4 other refineries could produce highway diesel fuel from their off-highway diesel fuel blendstocks for less than 5 cents per gallon. Production from these 6 refineries would increase highway diesel fuel production by 7 percent. Together with a more reasonable estimate of downgrades in the distribution system, this would more than compensate for any potential lost production, even as estimated by CRA.

CRA also implicitly assumed that the material it projected could be removed from the highway diesel market could be sold at a reasonable price. However, CRA did not analyze the impact of this additional supply on the prices which could be obtained in these markets, or even if these alternative markets could physically absorb all of this material. Much of this material is not diesel fuel, but poor quality blendstock. It is not clear that such material could be blended into non-highway diesel fuel and CRA did not analyze this likely problem. Our analyses, supported by a study by Muse, Stancil and Co., indicate that any substantial quantities of highway diesel fuel diverted to other markets will depress prices in those markets substantially.[§] Hydrotreating diesel fuel to meet the 15 ppm standard avoids these depressed prices, reducing the net cost of meeting the new standard. Since CRA only considered the cost to desulfurize highway diesel fuel, and ignored the added cost of dumping this fuel into markets with depressed prices, CRA's conclusions must be considered to be seriously flawed in this regard.

Furthermore, CRA ignored the fact that roughly 15 percent of today's highway diesel fuel is consumed in engines and furnaces not requiring this fuel. Any shortage of highway diesel fuel would lead many of these non-essential users to switch to nonroad diesel fuel or heating oil. Only limitations in the fuel distribution system would cause these users to continue to burn highway diesel fuel.

[§] "Alternate Markets for Highway Diesel Fuel Components," Muse, Stancil & Co., for Southwest Research Institute, for U.S. EPA, September, 2000.

These problems with CRA's analysis, plus the lack of detail available concerning the specifics of the study, lead us to reject the study's conclusions that there will be significant supply shortfalls under a 15 ppm sulfur standard.

Finally, if any potential for highway diesel fuel shortfalls exists by requiring all fuel to meet 15 ppm sulfur in 2006, as CRA's analysis suggests, we believe that allowing some continued supply of 500 ppm, as under the temporary compliance option and hardship provisions contained in today's action, addresses this concern. By allowing some transition period before the entire highway diesel pool is required to meet the 15 ppm sulfur standard, some refiners will not need to change their current operations and will be able to continue producing 500 ppm fuel during these years. Those refiners that delay production of low sulfur diesel fuel until the later years of the program will tend to be the refiners with the highest cost to comply and, thus, the greatest tendency not to invest and impact supply. Refiners that begin producing low sulfur diesel fuel in the later years of the program will be able to take advantage of ongoing improvements in desulfurization technology that will help avoid or reduce any potential losses in highway diesel fuel production when the program requires full compliance with low sulfur diesel fuel.

8. Conclusions

In order to meet the proposed 15 ppm sulfur cap, refiners are likely to further hydrotreat their highway diesel fuel in much the same way as it is being done today to meet the 500 ppm sulfur cap. Improvements to current hydrotreaters can be used to reduce diesel fuel sulfur beyond that being done to meet the 500 ppm cap. However, these improvements alone do not appear to be sufficient to provide compliance with the proposed 15 ppm cap. Based on past commercial experience, it is very possible to incorporate current distillate hydrotreaters into designs which provide compliance with the proposed 15 ppm cap. Thus, the equipment added to meet the 500 ppm standard in the early 1990's will continue to be very useful in meeting a more stringent standard.

The primary changes to refiners' current distillate hydrotreating systems would be:

- 1) the use of a second reactor to increase residence time, possibly incorporating counter-current flow characteristics, or the addition of a completely new second stage hydrotreater,
- 2) the use of more active catalysts, including those specially designed to desulfurize sterically hindered sulfur containing material,
- 3) greater hydrogen purity and less hydrogen sulfide in the recycle gas, and
- 4) possible use of higher pressure in the reactor.

Existing commercial hydrotreaters are already producing distillate with average sulfur levels below 10 ppm, which should be more than sufficient to meet a 15 ppm cap. These hydrotreaters are processing distillate with typical breakdowns of SRLGO, LCO and LCGO. Therefore, the proposed 15 ppm cap appears to be quite feasible given today's distillate processing technology. The only drawback of these commercial demonstrations is that they were designed to reduce aromatics content, or improve cetane, as well as reduce sulfur. Therefore, these units' hydrogen consumption and its associated cost are higher than that needed for simple sulfur removal. This combination of sulfur and aromatics reduction has been encouraged by fuel tax incentives in Europe. The incentive to reduce sulfur by itself to such low levels has not existed, so refiners have generally had no incentive to produce such a product commercially.

Advances continue to be made in catalyst technology, with greater amounts of sulfur being able to be removed at the same reactor size, temperature and pressure. Therefore, it is reasonable to expect that distillate hydrotreaters put into service in the 2006 timeframe will utilize even more active catalysts than those available today.

Other methods of reducing diesel fuel sulfur, such as FCC feed hydrotreating, removing the heavy end of LCO, etc. help to reduce diesel fuel sulfur levels, but will generally not be sufficient to provide compliance with a 15 ppm cap. However, we expect that a number of refiners will utilize these techniques to reduce the severity of their distillate hydrotreaters and reduce hydrogen consumption (particularly by avoiding aromatic saturation). Some of these techniques would tend to increase the supply of highway diesel fuel (e.g., FCC feed hydrotreating), while others would tend to decrease it (e.g., removing the heavy end of LCO).

Biodesulfurization technology holds promise to reduce distillate sulfur without the high temperatures and pressures involved in hydrotreating. Efforts are underway to demonstrate that this technology can achieve 50 ppm sulfur or less in the next few years. However, it is not clear whether this technology would be sufficient to meet a 15 ppm cap.

9. Fuel Availability in 2006

a. Summary

We analyzed the refining and finished products distribution industries to determine the minimum volume of 15 ppm diesel fuel that will assure it is widely available in all parts of the country by September 1, 2006 and still provide for the supply of a modest amount of 500 ppm fuel to mitigate concerns about supply shortfall. Small refiners, which contribute about 5 percent to the national highway diesel fuel supply, have been given the opportunity to defer production of 15 ppm fuel for four years. We investigated how much production of 15 ppm fuel by the remaining refiners would still assure adequate availability across the country. We determined

that at least 80 percent of the highway production within each PADD by non-small refiners must be converted to 15 ppm diesel to provide those assurances.

We feel it is important to understand, to the degree possible, how well balanced and operated the refining, supply, and distribution industries in this country are. Everyday 110 million gallons (2.6 million barrels) of diesel fuel (roughly 15 percent of total finished product volume) will be produced by refineries and distributed via pipeline, truck, and other means to end-users by the year 2006. These industries have developed and maintained a very efficient and safe, albeit complex, system for converting crude oil into finished products and making them available in the market at reasonable prices, especially compared with much of the rest of the world.

b. Diesel Fuel Refining Under the Temporary Compliance Option

There are currently 124 refineries in the country that produce highway diesel. Historically, the Pacific and Gulf coasts have had the highest concentration of both large and small refineries. For example, the refineries in Texas, Louisiana, and Mississippi, most of which are located near the Gulf, produce roughly 43 percent of the highway diesel in the country. The refineries in California, mostly located near the Pacific, produce about 12.5 percent of all highway diesel. On the other hand, all the refineries located in PADD I (the Atlantic coast region) produce about 6 percent of total highway diesel, and only 18 percent of expected PADD I highway demand. The others are “scattered” across the country, although some are clustered in certain regions or states, such as the Rocky Mountains, Kansas, Oklahoma, and Illinois.

There were two key considerations in our analysis of the refining industry. First, we projected which refineries would make the investment to convert to 15 ppm diesel and which would continue to produce 500 ppm fuel. Second, we evaluated where in each PADD each of the sets of refineries are located with respect to each other, to pipelines, terminals and other major fuel consuming markets.

We used the refinery cost model described in chapter V of the Regulatory Impact Analysis to predict which refineries would most likely make the investment to produce 15 ppm fuel. Early analysis showed a concentration of low cost refineries on the Gulf coast. Consequently, restrictions on averaging and trading were necessary to prevent 15 ppm fuel from being produced in limited areas of the country if wide spread availability was to be achieved. We considered various regional restrictions, but concluded that the PADD regions provide a good differentiation of the main fuel production and distribution regions of the country. Subsequent analyses were conducted assuming averaging and trading would only take place among refineries within each of the five PADD's. While the ABT program is PADD restricted, the transfer of fuel between PADD's is important and refinery location with respect to other PADD's was also considered. The small refiner hardship and GPA provisions of the rule were assumed in the base case in these analyses. With one exception, refiners were assumed to produce either 100 percent 15 ppm fuel or 100 percent 500 ppm fuel, based on our analysis of cost and on discussions with

various refiners. The one exception was those refineries with hydrocrackers that can produce 15 ppm diesel very cheaply from their hydrocrackate but otherwise produced 500 ppm diesel. We assumed that the “least-expensive-to-convert” refineries in each PADD would make the investment to produce 100 percent of 15 ppm fuel and that the remaining refineries would purchase available credits from them to continue producing 500 ppm diesel fuel. We want to stress that each refinery was studied as thoroughly and equitably as the available data allowed. With the exception of small changes from PADD to PADD due to varying numbers of small refiners and their volume, the PADD specific ABT restrictions result in essentially the same volume of 15 ppm produced within each PADD. Depending on the level of 500 ppm fuel allowed to be produced, however within each PADD production of 15 ppm fuel may be limited to certain areas. At an 80 percent level for 15 ppm fuel under the temporary compliance option, production of 15 ppm fuel is projected to occur on a widespread basis across all the PADD’s.

Table IV.A-8. Number of Refineries Producing 15 ppm Diesel by PADD

PADD I	3
PADD II	13
PADD III	24
PADD IV	8
PADD V	11

i. Pipelines, Terminals, and Bulk Plants

As important as it is for fuel availability for refineries to produce adequate volumes of 15 ppm fuel in all major regions of the country, it is equally important that pipelines handle that fuel. At present, large volumes of both highway (< 500 ppm total sulfur) and off-highway diesel (~3,000 ppm total sulfur) are transported long distances via pipeline to delivery or “break-out” terminals for distribution by bulk and tank truck. There are approximately 127 pipeline companies currently operating pipelines in the country. Trucking fuel over long distances is prohibitively expensive and logistically, nearly impossible. A case in point, is the transfer of fuel into PADD I from PADD III. The Plantation pipeline, which runs from Louisiana to Indiana can deliver 476,000 barrels per day. On the other hand, it would require 2,400 trucks, each carrying 200 barrels (8,400 gallons) to deliver that same volume, which includes running the trucks just one-way. The distances involved would make the cost for distribution by truck prohibitively high.

The experience and knowledge-base of the pipeline companies and shippers make it possible to ship batches of millions of gallons of different products, such as gasoline, jet fuel, kerosene, diesel, home heating oil down the same line, switching lines from time-to-time, cost-effectively, and with a minimum of problems. For example, over the course of a year, the Colonial Pipeline handles 38 different grades of gasoline, including reformulated gasoline and multiple vapor pressures for each grade, seven grades of kerosene (including two for military), 16 grades of home heating oil and diesel fuel (including marine diesel fuel for the U.S. Navy and light cycle oil) and one grade of transmix.. The Plantation Pipeline has a similar slate of finished products. While these pipelines carry multiple grades of fuel, their ability to add another fuel, especially in large volumes, is limited by tankage along the way. In that the northeast part of the country uses most of the home heating oil in the country, most other pipelines don't usually carry it on their slate. The TEPPCO Pipeline slate includes gasolines, distillates, commercial jet fuel, military jet fuel, unfinished gasoline, and speciality blendstocks. The Explorer Pipeline system transports primarily gasoline, fuel oil, and jet fuel. The Olympic Pipeline carries gasoline, diesel, and jet fuel. Generally, from the mid-west through the west, homes and businesses are heated with natural gas which precludes the need to ship heating oil.

Pipelines vary in lengths of from as little as a few thousand feet (the shorter sections are usually referred to as stub lines) to thousands of miles, including connections. For instance the Plantation system is 3,100 miles long; the Colonial system is about 4,300 miles long; the Chevron Pipe Line Company's network of pipelines is about 5,000 miles long, which includes their crude, chemical, and LPG capacity. The Olympic line is 400-miles, the Explorer 1,400-miles, and the Kanab 2,075-miles long.

Pipelines vary in diameter from 6 to 48-inches. For example the Plantation pipeline varies from 6 to 30-inches; the Colonial pipeline has segments that vary from 8-inches to 48-inches. The Explorer mainline pipe size is 28-inches from Port Arthur to Tulsa and 24-inches from Tulsa to Hammond, Indiana. Most pipelines ship liquids at velocities of from 4 to 7-miles per hour, or at an average of between 5 and 6-miles per hour. Capacities can be estimated using the diameter of the pipe. Average velocities are probably most useful, because sections of many pipelines vary in diameter. Velocities are also affected by the viscosities of the various products in the line. For example, the Plantation pipeline delivers about 476,000 barrels per day through their system. The Olympic ships about 306,000 barrels per day. Colonial pipeline's main line batch sizes vary from 75,000 to 3.2 million barrels. The smallest main line batch is 75,000 barrels. Explorer's 28-inch section has a capacity of over 500,000 barrels per day; it's 24-inch section can handle about 317,000 barrels per day.

Splitting the current single grade of highway diesel fuel into multiple grades raises concerns about the size of the batches that move through the pipelines. All pipelines, regardless of capacity, require minimum batch volumes to avoid the problems inherent with shipping small batches. For instance, the Colonial Pipeline has a minimum batch size of 75,000 barrels, while normal volumes range from 350,000 barrels or more per batch. The Plantation pipeline has a

minimum batch size of 25,000 barrels. The Chevron pipeline from Salt Lake City, Utah to Boise, Idaho has a minimum batch size of 6,000 barrels.

One problem with small batches is the speed with which they pass through a section of pipeline. In a 48-inch pipeline, 75,000 barrels would flow past a point in the line in just one and one-quarter hours. To break-out a shipment under these conditions requires extra-ordinary care and the possibility of contamination is high. Usually, the interface volume must be raised, which results in an increase in the loss of the higher quality, more valuable fuel, either to reprocessing or downgrading.

Most pipelines are common carriers and as such have fungibility requirements, usually referred to as pipeline specifications. That is, a shipper can ship a given volume of product, but in order to maximize the batch volume, a terminal will mix or co-mingle it with fuel from other shippers, such as from other refiners, that meet the same fungibility specification. At the destination terminal, the batch volume is “broken-out” into tanks from which bulk and tank trucks make deliveries. While this fuel will have characteristics similar to the fuel the shipper sent, it will not be “exactly the same fuel”, since batches of similar fuels were mixed with it at the origin of the shipment.

Another potential problem with small batches of 15ppm fuel is the need to “wrap” the fuel more carefully and differently than other fuels. “Wrapping” refers to the choice of products that precede and follow a particular batch of fuel in a pipeline. On the Explorer pipeline, a typical sequence would be fuel oils, diesel fuels, jet fuels, and gasolines. A typical sequence on the Colonial pipeline would be reformulated gasoline, low sulfur diesel, kerosene/jet fuel, high sulfur diesel, conventional regular gasoline, all premium grades, and reformulated regular gasoline. Each fuel is essentially “wrapped” by the fuel that precedes it and follows it. An efficient way to “wrap” is to ship two products next to each other, one of which can be “downgraded” to the other to avoid losing the interface to slop and reprocessing. For instance, when Jet A is shipped either ahead of or following 500 ppm diesel. A small volume of the Jet A can usually be downgraded to 500 ppm diesel, since it fits well within the highway diesel specs. It’s total sulfur content can be significantly higher, but the total volume of interface is usually small relative to the much larger diesel volumes and the small amount of extra sulfur can be lost to dilution. However, neither 500 ppm diesel nor 15 ppm diesel can be downgraded to Jet A because the high endpoint would drive the Jet A out-of-spec. Jet A, on the other hand, cannot be downgraded to 15 ppm diesel because it’s sulfur content can range as high as 3000 ppm. As a result, it is important to maximize the batch volumes of 15 ppm fuel, to the extent possible. The volume of interface relative to the shipment volume makes the cost of shipping small batches of 15 ppm fuel prohibitively high. See Chapter IV, D.2.a of the RIA for a complete discussion of pipeline interfaces.

We also considered whether we could expect the pipelines to handle 15 ppm diesel as a “proprietary” or “specialty” fuel and thus perhaps ship small batches and still make the fuel

widely and dependably available. Most pipelines will handle proprietary shipments (sometimes referred to as “tenders”) of certain products, but even then, the product usually has a specification range that fits well with the specs of other products shipped on the line and can be efficiently “wrapped”; interface losses are usually larger with tenders and extra tankage fees can add as much as one-half to three-quarters of a cent per gallon. Another problem is that tenders must usually fit into an established pipeline schedule. Consequently, it is difficult to rely on regular deliveries of these products. While this is not impossible, as a practical matter it is difficult because the pipelines are usually kept full on schedules up to a month or more in advance. We expect this approach to be prohibitively expensive as well as making it difficult to have 15 ppm fuel widely available at all times.

The pipelines which currently ship only one grade of diesel fuel are expected to continue doing so, until 15 ppm fuel becomes the predominant fuel. We expect them to switch to 15 ppm diesel as their only grade of fuel. A few companies, for instance the Williams, the Cenex, the Chevron, and the Pioneer pipelines in the Rocky Mountain area prefer to carry only one grade of diesel, usually highway, and simply add the required dye when the fuel is loaded on to trucks at the terminal and sell it as off-highway. Pipelines that carry highway and high-sulfur off-highway diesels are also expected to switch to 15 ppm diesel rather than carry three fuels. However, we also recognize that a few of the larger pipelines, such as the Colonial and Plantation, may choose to ship three fuels. It is important to understand that not all terminals are owned by the pipelines that deliver to or from them. Consequently, even though a pipeline may be willing to carry 15 ppm diesel in addition to 500 ppm diesel, there must be terminals in the appropriate locations along the pipeline that are capable of taking delivery of the product.

As such, an important element of this analysis is to determine at what volumes the pipelines and terminals will likely ship/handle sufficient volumes of 15 ppm diesel to make it widely available, either as the only diesel fuel or in conjunction with other higher-sulfur, diesel grade fuels. We anticipate that under the 80 percent temporary compliance option program that the vast majority of the pipelines will just carry 15 ppm fuel. Some of the larger pipelines may choose to carry both fuels, but will limit either the distance the 500 ppm fuel is carried or the number of breakout locations. For this reason, in our analysis we assumed that 500 ppm fuel will be sold in just 50 percent of the country.

Moving to terminals, an important distinction exists between the difficulties terminals face and those that pipelines face when deciding to carry 15 ppm diesel if the volume of the 15 ppm fuel is much less or even nearly equal to the volume of 500 ppm fuel. As discussed above, small batches, including minimum volume batches of 15 ppm fuel, are difficult to handle but in fact most the difficulties take place in and around the terminals. It is in fact, at the terminals where batches are sequenced into a line and broken out at delivery. Interfaces are also managed at the terminal. Once the batch of 15 ppm fuel is in the line, it travels much the same way other products do. Volume on the line does not necessarily change, since the 15 ppm fuel is displacing a matching volume of 500 ppm fuel. However, at the terminal, the 15 ppm fuel must be broken

out into tankage separate from the 500 ppm, which means that unless the terminal has an extra tank somewhere of sufficient volume to handle the product, a new one must be constructed. Switching back and forth between the fuels is definitely problematic, since very small volumes of 500 ppm fuel could easily drive the 15 ppm fuel out of spec.

Today, thousands of pipeline terminals make diesel fuel accessible to thousands of bulk and tanker trucks that can easily and economically deliver smaller volumes to bulk plants or service stations, truck stops, fleets, and other end-users over distances of up to 150 to 200 miles. For instance, the Plantation pipeline is connected to 130 shipper terminals in eight states. These terminals are owned by petroleum refiners, marketers, military, and commercial fuel users. Products are “tendered” to the system from nine refineries in Mississippi and Louisiana, from other products pipeline systems, and via marine facilities on the Mississippi River. TEPPCO has 21 product delivery terminals and 31 storage facilities in 12 states. The Explorer has major tankage and terminals at Port Arthur, Greenville and Grapevine, Texas; Glenpool, Oklahoma; Wood River, Illinois, and Hammond, Indiana, and serves 70 major populations centers in 16 states. The Kanab services parts of Wyoming, Colorado, North and South Dakota, Nebraska, Iowa, and Kansas. The TEPPCO system includes 21 product delivery terminals and 31 storage facilities in 12 states. The Olympic has 10 delivery stations between Anacortes, Washington and Portland, Oregon. These represent just a few examples of the roughly 1,400 storage facilities and terminals in the U.S.

At the production volumes and for the logistical reasons discussed above, the terminals which currently handle only one grade of diesel fuel are expected to switch to 15 ppm diesel rather than invest in the tankage and ancillary equipment necessary to carry two fuels. Discussion with and comments with industry suggest that very few, if any, terminals have unused tankage available to carry an extra fuel. A few of these companies actually supply some off-highway diesel but because they prefer to carry only one grade, usually highway, they simply add the required dye when the fuel is loaded on to trucks and sell it as off-highway. For example, some of the refineries in PADD IV supply off-highway diesel to the mining industry. Historically, most of the off-highway diesel in PADD IV has been relatively low sulfur and the refiners and shippers have simply sold dyed highway diesel into this market. We estimate that about 20 percent of the off-highway diesel in these areas is actually high sulfur fuel. Terminals that handle highway and high-sulfur off-highway diesels are also expected to switch their highway fuel to 15 ppm diesel rather than carry three fuels. However, we also recognize that the terminals on a limited number of the larger pipelines, such as the Colonial, Plantation, and perhaps the Explorer could choose to handle three fuels, and may need to build additional tankage. It is through these terminals that the remaining 500 ppm fuel would be distributed.

ii. Bulk Plants

In addition to terminals, there are roughly 10,000 bulk plant across the country which receive diesel fuel, usually by truck and then redistribute it in smaller quantities to retail outlets.

Many of the bulk plants are owned and operated by the owners of truck fleets and service stations and are major source of supply of diesel fuel, particularly in the rural areas of the country. Bulk plants typically have just one, roughly 20,000 gallon tank per product handled. As such, the introduction of another 20,000 gallon grade of diesel fuel would require the to either add tankage to carry both or specialize in supplying one or the other. At an 80 percent level for the temporary compliance option, with the 15 ppm fuel being the only fuel available except near refineries producing 500 ppm fuel or near those terminals that invest to distribute both fuels, we anticipate that most bulk plants will not add tankage and will merely switch over to 15 ppm fuel. Where available, 500 ppm fuel would likely be trucked directly from the terminal to the retail outlet or centrally fueled fleet without going through the bulk plant.

iii. Fleets & Card-locks

We expect fleet owners and card-lock companies will make the most economically reasonable choices available. They will likely purchase 500 ppm fuel, if it is available and even if it is only a penny cheaper, until they or their customers purchase a vehicle which requires 15 ppm fuel. At that time, we expect they will switch to 15 ppm fuel rather than build an extra tank, since all of their diesel powered vehicles can use the 15 ppm fuel. There was some discussion as to whether a fleet owner could arrange for a vehicle with the new emissions device to fill at a facility, i.e., another fleet owner, carrying 15 ppm fuel rather than convert his fleet to 15 ppm diesel. The proposition sounds simple, but in fact there are several costs involved. It is possible that the nearest sister facility is several miles distant, at times in heavy traffic, and perhaps in the direction opposite the one to be taken by the vehicle looking for the 15 ppm fuel. Distance and time are both important factors. For example, some drivers are paid by the load and would likely demand extra pay for time spent fueling a truck. Driving loaded trucks, at 4 to 5-miles per gallon (perhaps even lower in slow or heavy stop-and-go traffic) can quickly add several cents to each gallon of fuel purchased from a distant facility. We also considered whether a fleet owner could fuel at a service station. Most service stations are designed for light vehicles only and are often located in high traffic areas, such as at intersections. Unless the station owner installs special accommodations for large trucks, fueling would be nearly impossible. Many stations also do not have around-the-clock service. It was suggested that because some larger fleets have multiple fueling depots, an owner could assign vehicles with the new emissions device to a particular depot where 15 ppm fuel would be available. Flexibility is very often the key to success for a trucking company. We do not expect owners would spend hundreds of thousands of dollars for a new truck and then restrict it's use to a particular, confined region. Card-lock companies will likely also switch with demand for the 15 ppm fuel, rather than add facilities to handle two fuels.

iv. Truckstops

Truckstops depend on never having to turn away customers. The 15 ppm fuel can be sold to all customers while 500 ppm fuel can only be sold to the pre-2007 vehicles. Consequently, we expect that most truckstops would choose to begin carrying 15 ppm fuel at the start of the

program, particularly at an 80 percent requirement under the temporary compliance option where 500 ppm fuel may be in short supply. It was suggested that truckstops could easily de-manifold their current systems and incorporate 15 ppm fuel for sale with their 500 ppm fuel. Based on discussions with truckstop owners we learned that many of them take delivery multiple times a day to prevent their tanks from running dry. Because at some point, there would be equal demand for both fuels, half the tankage would need to be available for each fuel. However, at the beginning of the program the 15 ppm fuel would likely be in low demand, which would make it nearly impossible to keep the inventory of 500 ppm fuel from running out. An additional concern, is what it would cost in lost business to take the system down for the re-manifolding period at the beginning. However, truckstops are likely to be the location most capable of and have the greatest economic incentive to make both fuels available. Regardless, however, 15 ppm fuel should be available.

v. *Service Stations*

We expect most retailers, such as service stations, will switch to 15 ppm fuel rather than install extra tankage to carry both fuels, especially given the magnitude and brevity of the optional compliance period. While a limited number of retailers choose to sell only 500 ppm fuel, they risk turning away customers, since the actual price differential between 15 ppm and 500 ppm fuel in most markets under the 80 percent requirement is expected to be small. The risk of losing customers would likely outweigh any economic advantage for continuing to sell 500 ppm fuel.

vi. *Evaluation of Fuel Availability by PADD*

Essentially, our line of thinking and analysis was that if a majority of the refineries produce the 15 ppm fuel, and given that the majority of the major pipelines connected to these refineries, the fuel will be made available in quantities sufficient to widely distribute it through the bulk plants to retailers and other end users. We began the evaluation with PADD III since it supplies fuel into most of the other PADD's.

(1) PADD III

The total volume of diesel produced in PADD III is about 1.2 million barrels per day. Eighty percent of that or about 960,000 barrels per day of 15 ppm diesel will be produced by twenty-four refineries, most of which are located along the Gulf coast, although a few in other areas of the state will play an important role in assuring 15 ppm fuel is widely available, not only within PADD III, but also in PADD's I, II, and IV. Movement within the PADD is handled by companies such as the Longhorn, Koch, Ultramar Diamond Shamrock, Citgo, Conoco, Shell, Chevron, Mobil, Fina, Texaco, and Trust pipeline companies. At production volumes less than 80 percent, we estimated that at least one region of Texas may have difficulty receiving 15 ppm fuel, except by truck. At the lower production levels, the refineries in that area would likely

continue producing 500 ppm fuel, most of which would be exported into PADD's I and II; small volumes are also exported into PADD's IV and V. Since most, if not all the fuel from this region is flowing by pipeline out of the area, there is limited expectation that 15 ppm fuel would flow into the area by pipeline. At 80 percent production volume and for the reasons discussed above, we expect the fuel of choice for most pipelines will be 15 ppm fuel and that most retailers will carry the fuel. As noted above, this PADD is a significant source of diesel fuel for PADD's I and II.

(2) PADD I

Three refineries are predicted to produce about 135,000 barrels per day of 15 ppm diesel, which is 80 percent of the total highway diesel produced by refineries in PADD I. Although these refineries will produce more than enough 15 ppm fuel to meet first and even second year demand in the entire PADD, most of the fuel produced in PADD I comes from the area above Virginia. As such, it is usually distributed northward, northwestwards and northeastwards within the PADD, with some short-distance distribution southward, mostly by truck. To the extent that 500 ppm diesel is already shipped, mostly by truck, into the upper northeastern states today, it should not be difficult or expensive to replace that volume with 15 ppm fuel. We expect that at the production levels most retailers will carry 15 ppm diesel. Since highway diesel demand in PADD I is approximately 820,000 barrels per day, about 82 percent of it must be imported from PADD III, via the Colonial and Plantation pipelines and through foreign imports. For instance, a shipment on the Plantation pipeline takes about 20 days and costs approximately 2 cents per gallon to travel from Baton Rouge, Louisiana to the Washington D.C. area. Shipments on the Colonial are comparable both in time and price. In order to meet overall diesel demand, the pipelines will likely carry both 15 ppm and 500 ppm fuel.

(3) PADD II

The total volume of diesel produced in PADD II is about 682,000 barrels per day. Thirteen refineries, fairly strategically located in seven of the 13-PADD II states, are predicted to produce about 80 percent or 546,000 barrels per day of 15 ppm diesel. At this volume we expect the diesel of choice for the majority of pipelines will be the 15 ppm fuel and that most retailers will carry the fuel. The Kaneb, Amoco, Marathon Ashland, Buckeye, Countrymark, Conoco, Phillips, and Wolverine pipelines move much of the fuel around in this PADD. Most of the pipelines are hooked into refinery terminals but most also take delivery from and supply into the other pipelines. We found that at volumes less than 80 percent production, it was likely that two or three refineries in at least two strategic locations may not choose to produce 15 ppm fuel. In both cases these refineries were an important source of highway fuel for a fairly significant area. If they continued to produce 500 ppm fuel, it would likely stop, or at the very least hinder, the flow of sufficient 15 ppm fuel into those areas and prevent it from being widely available. At the 80 percent production level, sufficient fuel would be available in both areas. About 122,000 barrels per day of additional diesel must be imported, principally from PADD III. The Explorer,

Williams, Citgo, TEPPCO, Phillips, and Conoco pipelines play an important role in this transfer. For the reasons we discussed above, we expect the 15 ppm diesel will be the fuel of choice for the pipelines from PADD III. Considering the location of the refineries in this PADD and their access to pipelines which are expected to carry 15 ppm diesel, we expect the fuel will be widely available.

(4) PADD IV

The total volume of diesel produced in PADD IV is about 127,000 barrels per day. Eighty percent of that volume or about 101,000 barrels per day of 15 ppm diesel is projected to be produced by eight refineries. The Chevron, Pioneer, Conoco, Yellowstone, Cenex, and Kanab pipelines move most of the fuel in this PADD. This PADD makes up the majority of the GPA and has several small refineries that may choose wait until 2010 to make the investment to convert to 15 ppm fuel. We analyzed each pipeline with respect to the volume of 15 ppm fuel produced by refineries serving it. We were very concerned that, given the potential small refiner and GPA choices, there would be insufficient fuel to cause the pipelines and terminals to switch to 15 ppm fuel. We felt that parts of eastern Montana and Wyoming, western parts of North and South Dakota and an area in northeastern Montana may not receive enough 15 ppm fuel to make it widely available. At the 80 percent production requirement, we expect the fuel of choice for the pipelines will be 15 ppm diesel because it is the dominant fuel and that most retailers will carry the fuel.

(5) PADD V

PADD V has a few characteristics that make it somewhat different from the other PADD's. This is the only PADD that is really comprised of a number of separate and distinct fuel distribution systems; California, Arizona, and Nevada; Washington and Oregon, and Hawaii and Alaska. In California the SFPP, Shell, Mobil, and CalNev pipelines most of the diesel within the state. Las Vegas, Nevada is serviced via the CalNev. The southern part of Utah (PADD IV) is supplied from Las Vegas by truck. The SFPP services Reno and Fallon, Nevada in the north.

Another somewhat unusual condition exists in this PADD, in that the western halves of Washington and Oregon are somewhat isolated from service from either California or PADD IV. If PADD trading was widely permitted under a production requirement of less than 80 percent, it is possible that the refineries in the northwest could actually purchase credits and produce no 15 ppm fuel. Because the region is isolated from reasonable service out of either PADD IV or V, there would be no 15 ppm fuel in this area. At the 80 percent level, we expect that at least two refineries in the northwest will convert to produce 15 ppm fuel in volumes sufficient to meet demand for at least the first year or two. The Olympic pipeline connects the refineries in Washington with Portland, Oregon and the SFPP connects Portland to Eugene, Oregon. Due to the unique situation described earlier for this PADD, Alaska and Hawaii were split off from

PADD V and made their own trading area in order to ensure sufficient availability of 15 ppm fuel. Consequently, we expect most retailers and truckstops will switch to 15 ppm fuel for the reasons described above.

B. Interaction with Other Programs

In addition to the program proposed today, there are a number of other environmental programs that may concurrently have an impact on the refining industry. The most significant of these programs is the recently promulgated gasoline sulfur standards as part of the Tier 2 rulemaking. We have examined the impacts on engineering, construction, and capital expenditures of gasoline sulfur control in conjunction with the diesel sulfur control program .

A particular concern has been raised to the Agency regarding the capability of the engineering and construction (E&C) industries to be able to design and build diesel fuel hydrotreaters while at the same time doing the same for gasoline, as well as accomplishing their other objectives. Compliance with the 15 ppm sulfur cap for on-highway diesel fuel begins for refiners on June 1, 2006. This is within the timeframe of the phase-in of the Tier 2 sulfur standards applicable to gasoline. Thus, it is important to consider the requirements of complying with the diesel fuel sulfur cap in the context of the requirements of the Tier 2 gasoline sulfur standards. Two areas where it is important to consider the combined impact of two or more fuel quality specifications are: 1) refiners' ability to procure design and construction services and 2) refiners' ability to obtain the capital necessary for the construction of new equipment required to meet the new quality specification.

1. Design and Construction Services

We evaluated the requirement for engineering design and construction personnel, particularly three types of workers: front-end designers, detailed designers and construction workers, needed to implement the Tier 2 gasoline sulfur program and this diesel fuel sulfur cap. We developed estimates of the maximum number of each of these types of workers needed throughout the design and construction process and compare those figures to the number of personnel currently employed in these areas. It would also be useful to evaluate certain types of construction workers which might be in especially high demand, such as pipe-fitters and welders. However, good estimates of the number of people currently employed in these job categories are not available. Thus, it is not possible to determine how implementing the diesel fuel sulfur cap might stress these specific job categories.

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The number of job-hours necessary to design and build individual pieces of equipment and the number of pieces of equipment per project were taken from Moncrief and Ragsdale.^h Their paper summarizes analyses performed in support of the recent National Petroleum Council study of gasoline and diesel fuel desulfurization, as well as other potential fuel quality changes. These factors are summarized in Table IV.B-1.

Table IV.B-1. Design and Construction Factors for Desulfurization Equipment		
	<i>Gasoline</i>	<i>Diesel</i>
Number of New Pieces of Equipment per Refinery	60	15
Number of Revamped Pieces of Equipment per Refinery	0	30
<i>Job hours per piece of new equipment *</i>		
Front End Design	300	300
Detailed Design	1200	1200
Direct and indirect construction	9150	9150

* Revamped equipment estimated to require half as many hours per piece of equipment.

The gasoline sulfur standards as promulgated last year phase in between 2004 and 2008, with the potential for the generation of early sulfur reduction credits prior to 2004. However, a number of small refiners and refiners selling gasoline in the Geographic Phase-in Area are expected to take advantage of an option being afforded in this diesel fuel program. These refiners will be able to delay their compliance with the 30 ppm average, 80 ppm cap standards for gasoline for two years. Thus, the phase in of the Tier 2 gasoline sulfur program now extends from 2004 to as late as 2010 for GPA refiners and 2011 for qualifying small refiners.

The sulfur standards phase in at equal 12 month intervals effective on January 1 of each calendar year. Thus, it is convenient to break up the construction of gasoline desulfurization units by the year in which they have to become operational. Table IV.B-2 shows our projection of the number of gasoline desulfurization units which must be operational by January 1 of the indicated year.

^h Moncrief, Philip and Ralph Ragsdale, "Can the U.S. E&C Industry Meet the EPA's Low Sulfur Timetable," NPRA 2000 Annual Meeting, March 26-28, 2000, Paper No. AM-00-57.

Table IV.B-2. Number of Gasoline Desulfurization Units Becoming Operational on January 1 of the Indicated Year ⁱ							
<i>Prior to 2004</i>	<i>2004</i>	<i>2005</i>	<i>2006</i>	<i>2007</i>	<i>2008</i>	<i>2009</i>	<i>2010</i>
Gasoline Units: After Promulgation of the Tier 2 Gasoline Sulfur Program							
10	37	6	26	9	9		
Gasoline Units: After Promulgation of the Diesel Fuel Sulfur Program							
10	37	6	26	5	3	4	6
Diesel Units							
			63				58

The diesel fuel desulfurization units are projected to start either 2006 or 2010, according to the temporary compliance and hardship provisions. With respect to the required number of job-hours per unit, all of the gasoline units were assumed to be new, grassroots units. The diesel fuel units were assumed to be 80 percent revamps and 20 percent new, grassroots units, consistent with the analysis presented earlier in this chapter.

A worse case assumption would be that all of the units scheduled to start up on a particular January 1 began and completed their design and construction at the exact same time. However, this is not reasonable for a couple of reasons. One, an industry-wide analysis such as this one assumes that all projects take the same amount of effort and time. This means that each refinery is using every specific type of resource at exactly the same time as other refineries with the same start-up date. However, refineries' projects will differ in complexity and scope. Even if they all desired to complete their project on the same date, their projects would begin over a range of months. Thus, two projects scheduled to start up at exactly the same time are not likely to proceed through each step of the design and construction process at the same time. Second, the design and construction industries will likely provide refiners with economic incentives to avoid very temporary peaks in the demand for personnel. Thus, with respect to units starting up in a given year, we assumed that the design and construction of these units would be spread out throughout the year, with 25 percent of the units starting up per quarter. Given this assumption,

ⁱ Regulatory Impact Analysis - Control of Air Pollution from New Motor Vehicles: The Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements, U.S. EPA, December 1999, EPA 420-R-99-023.

we developed the breakdowns of personnel requirements by month for a given project shown in Table IV.B-3.

Table IV.B-3. Distribution of Personnel Requirements Throughout the Project			
	<i>Front-End Design</i>	<i>Detailed Engineering</i>	<i>Construction</i>
Duration per project ^j	6	11	14
Duration for projects starting up in a given calendar year	15	20	23
<i>Fraction of total hours expended per month from start of that portion of the project</i>			
1	0.050	0.020	0.030
2	0.050	0.030	0.030
3	0.050	0.040	0.030
4	0.078	0.040	0.040
5	0.078	0.040	0.040
6	0.078	0.050	0.040
7	0.078	0.050	0.040
8	0.078	0.060	0.050
9	0.078	0.065	0.050
10	0.078	0.075	0.055
11	0.078	0.075	0.055
12	0.078	0.075	0.060
13	0.050	0.060	0.060
14	0.050	0.060	0.055
15	0.050	0.050	0.055
16		0.050	0.050
17		0.040	0.050
18		0.040	0.040
19		0.030	0.040
20		0.020	0.040
21			0.030
22			0.030
23			0.030

^j Moncrief, Philip and Ralph Ragsdale, "Can the U.S. E&C Industry Meet the EPA's Low Sulfur Timetable," NPRA 2000 Annual Meeting, March 26-28, 2000, Paper No. AM-00-57.

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The fraction of total hours expended estimated in Table IV.B-3 was derived based on the following. Front end design typically takes six months to complete. If 25 percent of the refineries scheduled to start of in a given year start their projects every quarter, each subsequent group of the refineries starts when the previous group is halfway through their front end design. Overall, front end design for the four groups covers a period of 15 months, or 6 months for the first group plus 3 months for each of the three subsequent groups. In spreading this work out over the 15 months, we assumed that the total engineering effort would be roughly equal over the middle 9 months. The effort during the first and last 3 month period would be roughly two-thirds of that during the peak middle months. The same process was applied to the other two job categories.

Finally, we assumed that personnel were able to actively work 1877 hours per year, or at 90 percent of capacity assuming a 40 hour workweek.

Applying the above factors, we projected the maximum number of personnel needed in any given month for each type of job. The results are shown in Table IV.B-4, both assuming the availability and unavailability of the temporary compliance option. In addition to total personnel required, the percentage of the U.S. workforce currently employed in these areas is also shown.

Table IV.B-4. Maximum Monthly Demand for Personnel			
	<i>Front-End Design</i>	<i>Detailed Engineering</i>	<i>Construction</i>
Tier 2 Gasoline Sulfur Program As Promulgated			
Number of Workers	421	1,277	8,423
Percentage of Current Workforce *	22%	13%	5%
Gasoline Plus Diesel Fuel Programs: No Temporary Compliance Option			
Number of Workers	882	2,570	15,623
Percentage of Current Workforce *	46%	27%	10%
Gasoline Plus Diesel Fuel Programs: With Temporary Compliance Option			
Number of Workers	571	1,669	10,658
Percentage of Current Workforce *	30%	17%	7%

* Based on current employment in the U.S. Gulf Coast, assuming that half of all projects occur in the Gulf Coast.

As can be seen, the diesel fuel program without the temporary compliance option would have had a large, impact on the required amount of E&C resources compared to only the Tier 2 gasoline program. Employment required in all three job categories would have essentially doubled with the addition of the diesel fuel program. However, with the temporary compliance option, the impact of the diesel fuel program is reduced dramatically, to the point where the required resources for the two programs are only about 30 percent greater than those of the Tier 2 gasoline program alone.

With the temporary compliance option, the largest impact is on front end design, where 30 percent of available U.S. resources are required. Thus, we believe that the E&C industry is capable of supplying the oil refining industry with the equipment necessary to comply with the proposed diesel fuel sulfur cap on time. We believe that this is facilitated by the extended phase-in we allowed regarding compliance with the Tier 2 gasoline sulfur standards and the diesel sulfur cap.

The second aspect of the aggregate impact of the proposed diesel fuel sulfur cap and other rules on refiners is their ability to procure adequate capital to fund the required investment in

new desulfurization equipment. Estimates of previous capital investments by the oil refining industry for the purpose of environmental control are available from two sources: the Energy Information Administration (EIA) and the American Petroleum Institute (API).

According to EIA, capital investment by the 24 largest oil refiners for environmental purposes peaked at \$2 billion per year during the early 1990's.^k Total capital investment by refiners for other purposes was in the \$2-3 billion per year range during this timeframe. API estimates somewhat higher capital investments for environmental purposes, with peaks of about \$3 billion in 1992-1993.^l

In the Tier 2 gasoline sulfur control rule, we estimated the expenditure of capital for gasoline desulfurization by year according to the phase in schedule described above.^m In that analysis, we simply assumed that all of the capital investment occurred in the calendar year prior to the requirement that the unit be on-stream. Here, we developed a somewhat more sophisticated schedule for the expenditure of capital throughout a project. We projected that the capital investment would be spread evenly over a 24 month period prior to the date on which the unit must be on-stream. The results are shown in Table IV.B-5.

^k Rasmussen, Jon A., "The Impact of Environmental Compliance Costs on U.S. Refining Profitability," EIA, October 29, 1997.

^l API Reported Refining and Marketing Capital Investment 1990-1998.

^m Regulatory Impact Analysis - Control of Air Pollution from New Motor Vehicles: The Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements, U.S. EPA, December 1999, EPA 420-R-99-023.

<i>Calendar Year</i>	<i>Gasoline</i>	<i>Diesel Fuel**</i>	<i>Total</i>
2002	1.7*		1.7
2003	1.11*		1.11
2004	0.85	1.3	2.15
2005	0.59	1.9	2.49
2006	0.15	0.7	0.85
2007	0.06		0.06
2008	0.06	0.5	0.56
2009	0.02	0.9	0.92
2010		0.2	0.2

* Includes capital related to the construction of desulfurization units built prior to 2004 for the generation of early credits.

As can be seen, capital investment peaks in 2004 and 2005, at \$2.15-2.49 billion. This is about two-thirds the previous high levels of refining industry investment for meeting environmental programs experienced during 1992-1994.³⁹ Therefore, this level of investment should be sustainable for a couple of years, particularly since the required level of investment drops off dramatically after 2006, and inflation has degraded the value of money somewhat since the early 90's. From 2002-2005, the required level of investment averages somewhat below \$2.0 billion per year, or about one-half of the levels experienced during the early 1990's.

In addition to gasoline sulfur control there are other environmental programs that could also concurrently have an impact on the refining industry. The phase-down of MTBE from gasoline is currently under consideration. While the nature of the action on MTBE has not yet been determined, if EPA acts to reduce or eliminate MTBE usage, we will consider cost impacts on refiners and provide sufficient lead time to comply with such requirements.

C. The Need for Lubricity Additives

Note that much of the discussion in this section on lubricity was obtained from two Society of Automobile Engineers (SAE) Technical Papers.⁴⁰ They are referenced here once to avoid numerous repetitive references in the text. Also, some studies are noted in the text without references. These studies, unless otherwise noted, are also extracted from these two SAE papers.

1. What Impacts Will the Sulfur Change Have on Lubricity?

Diesel fuel lubricity is the characteristic of diesel fuel to provide sufficient lubrication to protect each of the many contact types within fuel pumps and injection systems for reliable performance. Unit injector systems and in-line pumps, commonly used in heavy-duty engines, are actuated by cams lubricated with crankcase oil, and have minimal sensitivity to fuel lubricity. However, rotary and distributor type pumps, commonly used in light and medium duty diesel engines, are completely fuel lubricated, resulting in high sensitivity to fuel lubricity. Low fuel lubricity has been associated with low-viscosity fuels, such as No.1 diesel fuel or kerosenes, which are typically used in cold climates. As a result, many rotary fuel injection systems intended for use in cold climates contain components manufactured using improved metallurgy specifically to tolerate the use of poorer lubricity fuels.

Experience has shown that it is very rare for a naturally high-sulfur fuel to have poor lubricity, although most studies show relatively poor overall correlation between sulfur content and lubricity. One study indicated a relationship between diesel fuel lubricity and the content and composition of sulfur compounds. However, the artificial addition of sulfur compounds seems to have no effect or even a slight detrimental effect at high concentrations. Another study showed that fully-saturated hetrocyclic sulfur compounds are the most active naturally occurring fuel lubricity agents. High molecular weight components, back-end volatility, naphthalenes, polyaromatics, nitrogen compounds, polar compounds (excluding sulfur and nitrogen compounds) and oxygen compounds have been identified as potential lubricity agents. There is some indicated correlation between total aromatics content and lubricity, as measured by laboratory tests. The addition of aliphatic kerosene fractions to diesel fuel, which have inherently lower lubricity, can also decrease the lubricity of the resulting blend.

Unfortunately, few consistent trends are visible in the literature, and some researchers have shown that properties such as sulfur, aromatics, acidity and olefin content cannot be used alone to predict fuel lubricity. At present, the most that can be said definitively regarding the impact of fuel composition on lubricity is that a single fuel with low viscosity, low sulfur, aromatics and acid content generally will tend to have poorer lubricity than those with higher levels. Considerable research remains to be performed regarding the fuel components most responsible for lubricity. Consequently, successful application of either a chemical test or predictive model depends on a better understanding of the fuel and additive components responsible for lubricity.

Hydrotreating, in addition to reducing sulfur content, can lead to a reduction in the concentration of various compounds which may contribute to fuel lubricity such as aromatics and high molecular weight hydrocarbons. As early as 1976, it was suggested that lowering the level of aromatics, separation of sulfur compounds and polar substances, as well as separation of

surface-active substances during the hydrotreating refining process, can result in a reduction of the lubrication qualities of the fuel. One report⁴¹ suggested that reduction in lubricity is caused by the removal of the sulfur that itself acts as a lubricant, and the removal of some compounds such as furans, pyroles and thiophenes in the refining process. In one 1992-93 study, extremely low aromatics content produced by hydrotreating caused catastrophic failure of rotary fuel injection pumps. Unfortunately, few consistent trends are visible in the literature, and some researchers have shown that properties such as sulfur, aromatics, acidity and olefin content cannot be used alone to predict fuel lubricity.

Similarly, the aviation community has investigated the lubricity of jet fuel. The most satisfactory explanation for wear on failed aviation components has been a simple corrosive process, involving the repeated formation and removal of metal oxides during sliding. To a lesser extent, wear has been explained by severe adhesive wear and scuffing as the component dimensions were reduced beyond tolerable limits or if contact loads were unusually high. Severe refinery treatment removes the naturally occurring corrosion inhibitors from the fuel, allowing formation of a thick oxide layer. The removal of chemically active species to upgrade thermal stability was found to be associated with poorer fuel lubricity. A number of studies by the middle to late 1960s indicated that poor performance of high-purity jet fuel appeared to be related to the availability of naturally occurring compounds, rather than gross physical or chemical properties. Other studies indicated that fully saturated hetrocyclic compounds and polynuclear aromatic hydrocarbons have a beneficial effect on lubricating characteristics. As little as two percent aromatics greatly increased the load-carrying capacity of paraffins. Mixtures of heavy aromatics and paraffins were much more effective than either compound used alone. One study also found complex esters and, to a lesser extent, high molecular weight polymers to be effective as anti-wear agents in turbine and diesel fuel. Another study found that the lubricity of severely refined fuels could be improved by the addition of trace concentrations of surface-active additives, such as corrosion inhibitors.

Some studies have indicated that the presence of water may have a significant effect on lubricity values, although apparently only humidity values were monitored and controlled for those studies. The U.S. Navy conducted a study to determine the effects of humidity and water on distillate lubricity using the BOCLE, SLBOCLE, and HFRR tests⁴² (these tests are described in the next subsection). The results of this study indicated that the test fuels were not noticeably affected by any of the water introduction methods using any of the three test procedures.

Notwithstanding all these uncertainties, hydrotreating has been known to reduce the lubricity of the treated fuel, depending on the severity of the treatment and characteristics of the crude. If as anticipated, refiners increase the severity of their hydrotreating to comply with the 15 ppm sulfur standard, the lubricity of some batches of fuel may be reduced compared to today's levels. To compensate for the potential impact on fuel lubricity, we have accounted for an increased use of lubricity additives in highway diesel fuel in our cost calculations.

2. How Can One Determine Whether the Lubricity of a Fuel Is Adequate?

Many researchers have demonstrated that the correlation between the different wear mechanisms in fuel pumps is dependent on the fuel composition. This is particularly important for dissimilar wear mechanisms, such as oxidative corrosion and adhesive scuffing. The most successful wear tests appear to be those that reproduce the predominant (i.e., the most damaging) wear mechanisms. However, there is considerable disagreement as to the relevant importance of each mechanism and also to the appropriate laboratory-scale test procedure to measure lubricity. A number of studies have observed poor correlation between pump wear and the most widely used laboratory test procedures, and no single wear test provides a complete description of lubricity. In addition, these tests appear less effective when evaluating fuels that contain additives, compared to the base fuels. Several studies have reported that the laboratory tests predict negligible benefits from lubricity additives, but fuel trials indicate that lubricity additives do provide acceptable lubricity.

Many laboratory fuel tests which are designed to operate under boundary lubricating conditions are strongly correlated to viscosity. For many crude sources, a disproportionate fraction of sulfur-containing compounds are contained in the higher molecular weight fuel components, indicating an intrinsic relationship between chemical and physical fuel characteristics. One researcher successfully developed a simple empirical relationship that predicted fuel lubricity as measured using the SLBOCLE test (described below) using viscosity and di-aromatic content. Unfortunately, such a model does not account for the effects of trace constituents or lubricity additives. In 1993, the U.S. Army systematically defined the principal wear mechanisms as oxidative corrosion, chemical corrosion, adhesion, and scuffing (severe adhesion), with oxidative and scuffing predominating. In that study, the degree of pump wear seemed to be highly sensitive to the availability of dissolved moisture, indicating the presence of an oxidative mechanism.

The BOCLE (Ball-on-Cylinder Lubricity Evaluator) apparatus uses a ball-on-rotating cylinder contact geometry. The primary wear mechanism produced by this test was found to be oxidative corrosion and possibly the chemical corrosion mechanism found in high-sulfur fuels. The U.S. Army sponsored development of a modified BOCLE - the SLBOCLE (Scuffing Load Ball-on-Cylinder Lubricity Evaluator) - in 1994, to measure fuel load-carrying capacity. It measures the applied load required to produce a transition from mild boundary lubricated wear to adhesive scuffing. To minimize the effects of oxidative corrosion and abrasive wear, the SLBOCLE uses a polished test ring in place of a ground specimen. A Society of Automobile Engineers (SAE) paper concluded that the SLBOCLE test is a good tool to evaluate the lubricity of base fuels, which contain no lubricity additive.⁴³ However, this method can distinguish additives only if large amounts are used, well above the concentrations required to protect the equipment.

The HFRR (High Frequency Reciprocating Rig) was developed in Europe in 1986. The apparatus consists of a AISI E52100 steel ball, which reciprocates against a polished plate of the same material. The mean wear scar diameter formed on the ball is used as a measure of lubricity. This test produces a very wide range of wear mechanisms, depending on the fuel being evaluated. However, SAE paper 961948 concludes that the correlation between fuel injection pump rig and HFRR results have not been satisfactory. Many fuels which were regarded good according to a pump demerit wear rating were regarded poor according to the HFRR.

In 1991, the Society of Automotive Engineers (SAE) formed a committee to evaluate the effects of reduced fuel lubricity and to identify an effective laboratory wear test procedure. In Europe, the Coordinating European Council (CEC) was established for the same purpose. In 1992, both groups cooperated under the auspices of an International Standards Organization (ISO) working group. Following a systematic evaluation of the available test procedures, the group performed a round robin test program to compare the HFRR, two variants of the BOCLE, and the Falex BOTS (Ball-on-Three Seats) test. This work was backed up by full-scale pump tests performed by the original equipment manufacturers using a matrix of 12 fuels. A HFRR result of 450 microns was recommended by the ISO working group, and 460 microns by the CEC, as the maximum result for acceptable lubricity. No official minimum SLBOCLE result has been defined, but the ISO working group data and most studies indicate that an SLBOCLE result of approximately 3,000 grams delineates the transition between acceptable and poor lubricity. The ISO is involved in a Phase 2 study to include additized fuels, which were largely ignored in the original study. The objective is to evaluate the correlation between injection equipment rig tests and the HFRR test for additized fuels. No conclusion was reached at the time of publication of SAE 1999-01-1479 in May 1999.

The American Society for Testing and Materials (ASTM) lubricity task force evaluated the information that had been generated by previous working groups, including ISO, and recommended that the SLBOCLE and HFRR tests be adopted as ASTM test methods. However, the ASTM group chose not to adopt ISO's 450 micron specification and has not included a minimum lubricity requirement in ASTM D-975 specifications for diesel fuel quality. In addition to the additive problem, the two ASTM test methods (SLBOCLE and HFRR) suffer from poor precision and do not correlate well with each other. The ASTM group decided it needed to conduct more work to improve the precision of the test methods, resolve the discrepancy between the test results and the actual field experience, and modify the test methods to apply to additized fuels. A fuel specification will be considered after the test issues are resolved. The ASTM group is evaluating a recent BOTD (Ball on Three Disks) test, along with a modification to the existing HFRR method.

Chevron conducted a limited number of tests with additized fuels. In all cases, the HFRR test was indicated to be the least responsive to additive concentrations. This method does not recognize the existence of any additive up to levels above 100 ppm, and full benefit is indicated at levels between 200 and 500 ppm. The SLBOCLE test recognizes an additive effect

between 40 and 50 ppm, and detects the full potential of the additive between 50 and 200 ppm. The BOTD test recognizes an additive effect at a level as low as 10 ppm, and detects the full additive potential at around 20 to 40 ppm. Early reports by a recent effort at Southwest Research Institute indicate that the HFRR test discrimination of additized fuels could be improved by changes to the frequency and stroke.

3. What Experience Has There Been with Low-sulfur Fuels?

What has been the experience with aviation turbine engines?

Aviation turbine kerosene (Jet A, Jet A-1) is the principle fuel used by commercial airlines. A wide cut fuel spanning the gasoline and kerosene boiling range (JP-4, Jet B) has historically been used by many national air forces. A higher flash point fuel (JP-5) has been used for naval aircraft. Compared to both low and high sulfur diesel fuels, aviation kerosene fuels tend to be poor lubricants.

In 1969, the British Ministry of Defense formed a Fuel Lubricity Panel to specify a lubricity parameter for aviation turbine fuel. The Panel was unable to specify a lubricity test that would accurately reflect the lubricity requirements of an aviation turbine fuel, but it did suggest that a ball-on-cylinder machine showed promise. In the mid-1970's, the U.S. Navy began to experience durability problems on equipment operated with fuels from refineries outside the continental U.S. Failures were reported for afterburner hydrolic fuel pumps and also hang-up of fuel controls. The U.S. Navy in cooperation with the Coordinating Research Council (CRC) Aviation Fuel Lubricity Group began a detailed evaluation of the BOCLE apparatus. That study recommended that the BOCLE apparatus continue to be used to evaluate lubricity of fuels from the aircraft fleet, as well as the use of corrosion inhibitors in military aviation fuels. The study also recommended that new aircraft and fuel system components be developed to operate satisfactorily on low-lubricity fuel.

Since 1975, the approach of the commercial aviation community has been to maximize equipment durability through improved materials and design, rather than through control or measurement of fuel lubricating characteristics. However, the approach of the military has been to add corrosion inhibitors to the fuel. Currently, many military aircraft use JP-8 fuel, which is generally equivalent to Jet A-1 treated with several additives, including a corrosion inhibitor to improve lubricity. As a result of these efforts, the aviation community has reported only isolated problems related to lubricity. Research is in progress relating to future advanced turbine engines in which the incoming fuel will be exposed to temperatures reaching 163 °C and as high as 315 °C.

What has been the experience with compression ignition engines?

Unit injector systems and in-line pumps are actuated by cams lubricated with crankcase oil, and have minimal sensitivity to fuel lubricity. Rotary and distributor type pumps, commonly used in light- and medium-duty diesel engines, are completely fuel lubricated, resulting in high sensitivity to the effects of lubricity. As a result, the rotary fuel injection system has been the primary focus of lubricity research. As noted as far back as 1970, blending diesel fuel with a small concentration of good lubricity fuel has a disproportionately large effect on the wear characteristics of a blend. Blending or mixing different fuels minimizes the effect of isolated poor lubricity products. It has been observed that most equipment failures occur in fleets that are supplied from a single fuel source.

What has been the experience of the U.S. Military?

Military vehicles are particularly susceptible to the effects of fuel lubricity, as a given post or camp or station will use fuel from a single supplier for a minimum contract period of 12 months. As a result, little potential exists for blending of fuels from different sources. In addition, due to harsher operating conditions, engines used in military vehicles (especially tactical vehicles) are more vulnerable to lubricity problems than the equivalent engines operated in commercial vehicles.⁴⁴ In the 1970s, the Army approved JP-5 as an alternative to DF-2 (VV-F-800) diesel fuel. In the 1980s, the Department of Defense (DOD) adopted a single fuel for the battlefield and converted its tactical fleet of compression ignition powered vehicles from DF-2 to aviation turbine fuel (MIL-T-83133). In March 1988, DOD specified JP-8 as the primary fuel support for overseas ground forces, but considered it and Jet A-1 equivalent fuels. Jet A-1 does not contain the corrosion inhibitor additives of the JP-8 fuels. During Operation Desert Storm, the military experienced rotary diesel fuel pump failures on its vehicles when operated on Jet A-1. While examinations of the failed fuel injection components indicated the majority of failures were attributed to causes other than lubricity, the Jet A-1 did appear to produce increased wear in some areas of the pumps. Tests performed with rotary injection pumps on a motorized test stand indicated very severe wear was produced with Jet A-1 in as little as eight hours. Wear rate was significantly reduced by the corrosion inhibitors specified for use in JP-8. Subsequently, the U.S. military no longer considered those fuels to be equivalent.

The military noticed vehicle fuel system component wear when fuels with a SLBOCLE value of less than 2,000 grams were used consistently. The wear became significant for fuels with a SLBOCLE value of less than 1,600 grams. The DOD indicates in its comments to the proposed rule that, since the introduction of 500 ppm sulfur diesel fuel in the United States in 1993, it has experienced lubricity problems particularly in the Midwest and Northwestern portion of the United States, especially during the winter season. As a result, seven military bases require lubricity additives in the diesel fuel they procure during the winter months.

What has been the experience of the U.S. commercial sector?

According to the literature, no widespread failures associated with poor fuel lubricity have been reported in the United States, although on average, its diesel fuel has borderline lubricity, based on the HFRR test. However, a few commenters indicated experience of lubricity problems with existing diesel fuel, particularly in the United States. Fuel sulfur levels have been restricted to 500 ppm nationwide since 1993, except for Alaska and certain territories. In commercial vehicles, the beneficial effect of blending different fuels is likely to occur.

When lubricity has been a problem, failures that have been reported involved the use of No. 1 type diesel fuels with viscosities below 2.0 cSt at 40°C. Very low ambient temperatures, aside from the obvious effect on viscosity, greatly reduces the solubility of moisture in the fuel. Dissolved moisture is necessary for the oxidative corrosion wear mechanism to occur. Many rotary fuel injection systems intended for use in cold climates contain components manufactured using improved metallurgy specifically for this reason. Many municipal bus fleets in the continental United States operate year round using low viscosity diesel fuel, such as DF-1, to minimize exhaust emissions. In practice, many operators procure aviation kerosene fuels, particularly in more temperate southern areas where low viscosity diesel fuel is not readily available. Anecdotal reports of injection system failures with these fuels are relatively common, with replacements occurring as early as 15,000 miles in some instances.

What has been California's experience?

Low sulfur (500 ppm) diesel fuels have been marketed in Southern California since 1988. Beginning October 1993, diesel fuels marketed in all of California had to meet the new Federal sulfur standard of 500 ppm and a new state requirement of 10 percent aromatics by volume, or equivalent emissions. On average, the sulfur content of California's diesel fuel is about 140 ppm. In 1989, a few researchers, including fuel suppliers and engine and equipment manufacturers, recognized that the regulations to reduce the aromatics content in 1993 would have the potential to affect equipment if the fuel lubricity was reduced substantially. Of particular concern was the protection of rotary distributor pumps used in passenger cars, light vans and trucks, and much of California's agricultural equipment.⁴⁵

A Governor's Task Force on diesel fuel was created to investigate concerns regarding lubricity and other properties of the reformulated fuel. As a result, for three years from October 1993 through 1996, staff of the California Air Resources Board monitored fuel injection system problems (and also price increases and reports of supply shortages), and recommended that fuel suppliers monitor the lubricity of their fuel using the U.S. Army's SLBOCLE test or other appropriate test and add lubricity enhancing additives to diesel fuel with a SLBOCLE test result below 3,000 grams. The 3,000 gram level was a compromise between the 2,220 gram level suggested by the American Petroleum Institute (API) and the 3,330 gram level requested by Engine Manufacturers Association (EMA). Diesel fuels marketed in California are blended from

various refinery products and contain lubricity enhancers and other additives. As previously discussed, the SLBOCLE test lacks precision in evaluating additized fuels and underestimates the benefit of lubricity additives. Thus, the test results were considered an indication of the lubricity of the base fuel, and a worse case of actual fuel lubricity. Cetane-enhanced alternative formulation fuels, with aromatic content near 20 percent, were not hydrogenated as severely, and thus were not as dependent on additives for acceptable lubricity.⁴⁶

During the three year monitoring period of 1993-1996, no lubricity-related fuel pump damage was documented for diesel vehicles using California fuel. Also, analysis of the data showed no strong correlation of lubricity with either sulfur or aromatic content. At first, only 30 percent of the fuels evaluated met or exceeded the 3,000 gram level. The average SLBOCLE results for California fuels increased from 2700 grams in 1993 to 3,300 grams in 1996. This improvement may be attributed to use of lubricity additives, combined with increasing production of alternative formulations and blended products, which perform better on the SLBOCLE test than do low aromatic products with lubricity additives.⁴⁷

What has been Canada's experience?

Overall, Canadian fuels tend to have low density, low viscosity, and lighter distillation characteristics than those used in the United States, and are among the worst lubricity fuels in the world. Diesel fuel No. 1, as used for much of the year in Canada, is broadly similar to the kerosene fuels that caused durability problems in military vehicles, municipal buses, and aviation equipment. Even prior to the introduction of low-sulfur diesel fuel, Canada had reported problems with reduced equipment life. These failures were typically associated with winter grade diesel fuels, particularly when they were used in warmer conditions. Low-sulfur fuels have been available in Canada since the 1980s, and a maximum sulfur content of 500 ppm was mandated in 1994. Fleet testing repeatedly demonstrated catastrophic pump failure in less than 500 miles of operation on Canadian fuel. In 1997, Canada modified its low-sulfur diesel fuel specification to address the lubricity of winter fuels - those having a viscosity below 1.9 cSt at 40°C or less and a cloud point of -30°C or lower. A fuel supplier can "qualify" its fuel using one of several options, ranging from a field test to pump rig tests to the HFRR or BOCLE laboratory scale test. A fuel supplier must use lubricity additives if the fuel fails the selected test.

What has been Sweden's experience?

Beginning in 1991, Sweden required very low concentrations of sulfur and aromatics in its diesel fuels: maximum of 10 ppm sulfur and 5 percent by volume aromatics for Class I fuel, and maximum of 50 ppm sulfur and 20 percent by volume aromatics for Class II fuel. Field trials and research conducted by the fuel producers and equipment manufacturers indicated that these fuels, without additives, would produce unacceptable wear of light-duty injection systems. Failure of test rotary fuel pumps occurred between 5,000 and 19,000 miles for Class I fuel, and between 8,000 and 48,000 miles Class II fuel. Heavy-duty in-line pumps were less susceptible to

low lubricity fuel. This experience drew more attention and interest to the possibility of a widespread fuel lubricity problem in the rest of Europe and in North America at the time they were introducing their lower sulfur and lower aromatic fuels. Since that time the use of lubricity additives in Sweden's fuel has resulted in acceptable equipment durability.⁴⁸ Beginning in 1995, Sweden required nonroad equipment, excluding commercial boats, railroads, and stationary engines, to use the very low sulfur diesel fuel (which, as noted above, includes the lubricity additives). The use of the very low sulfur diesel fuel in nonroad applications in Sweden has not resulted in any equipment durability problems.

What has been Great Britain's experience?

Since 1998, due to the use of tax incentives, nearly all highway diesel fuel in Great Britain has met a 50 ppm sulfur level. A lubricity additive is added to the fuel. The use of the low sulfur fuel in on-highway trucks in Great Britain has resulted in acceptable equipment durability. Although nonroad diesel fuel in Great Britain is not low sulfur, a limited number of applications do use the low sulfur diesel fuel. The use of low sulfur diesel fuel in nonroad applications in Great Britain has not resulted in any equipment durability problems.

What has been the Experience in Asia and in South-Pacific Countries?

In the Far East, a number of countries have already or will soon implement a 500 ppm sulfur maximum: Korea in 1996, Japan in 1997, Hong Kong in 1997, Taiwan in 1999, Thailand in 1999, Philippines in 2000. In addition, Australia in 2003, and New Zealand in 2005 will implement a 500 ppm sulfur maximum. Research is being performed to determine the effects of Asian low-sulfur fuel on injection system durability, and except for one study in Thailand, results have not yet been published.

In Thailand, a field study was conducted to investigate the effects of low-sulfur diesel fuel (500 ppm) without lubricity additives on rotary injector pumps operating in actual driving conditions in Thailand.⁴⁹ The study involved three vehicles each for two fuels for 30,000 km. The first fuel was imported and made up of a blend of U.S. West Coast, Malaysian and locally refined fuel having a HFRR test value of 358 μm . The second fuel was the first batch of locally produced off highway fuel with a HFRR test value of 467 μm . Evidence of wear at the end of the study were within the normal acceptable range of wear at 30,000 km for all six pumps, although the pumps operated on the locally refined fuel showed nearly twice as much wear, on average, as the pumps operated on the imported blend.

4. What Can Be Done About Poor Lubricity Fuels?

Blending poor lubricity diesel fuel with a small concentration of good lubricity fuel has a disproportionately large effect on the wear characteristics of the blend. Thus, blending or mixing

different batches of diesel fuel, such as that which occurs in the commercial market in the United States, minimizes the effect of isolated poor lubricity fuels.

Also, blending small amounts of lubricity enhancing additives has increased the lubricity of poor-lubricity fuels to acceptable levels. Laboratory testing, field experience and controlled pump and vehicle testing indicate that additives can be effective in reducing pump wear. The lubricity additives widely used in diesel fuels range from the corrosion inhibitors used in aviation turbine fuel to fully synthetic non-acidic products. The additives' impact on pump wear appears to be strongly influenced by fuel composition and distillation characteristics, with larger improvements observed for poorer lubricity fuels. According to contacts in the industry and an SAE report, refiners are likely blending additives to diesel fuel on a batch-to-batch basis when poor lubricity fuel is expected. In one comment to the proposal, a producer of fuel systems confirmed that much of the U.S. diesel fuel today contains lubricity enhancing additives, including military fuels.

Sweden, Canada, and the U.S. military offer examples of experiences using additives to improve the lubricity of diesel fuel. Since 1991, the use of lubricity additives in Sweden's fuel has resulted in acceptable equipment durability.⁵⁰ Since 1997, Canada has required that diesel fuel not meeting a minimum lubricity be treated with lubricity additives. The U.S. military has found that traditional corrosion inhibitor additives that it uses, such as di-linoleic acid, have been highly effective in reducing fuel system component wear. Consequently, the U.S. Army now blends 250 mg/L of MIL-I-25017E corrosion inhibitor additive to all fuels that show a SLBOCLE result below 2,000 grams, and regularly for Jet A-1, JP-5 and JP-8 fuels. In addition, seven military bases that procure commercial fuel from the Midwest and Northwestern portion of the United States require lubricity additives, especially for that fuel they procure during the winter months.

According to the literature, lubricity additives have not been found to significantly affect exhaust emissions. However, adding too much can produce unwanted side effects, such as deposits in in-line injection pumps, fuel filter plugging, injector tip deposits, plunger sticking, and water haze problems. For these reasons, the selection and treat rate of an additive are important. An SAE report indicated it is likely that the more recently developed non-acid based additives provide improved performance with reduced problems from lubricant interaction. For example, in early 1996, field problems occurred in Western Europe with vehicles fitted with in-line diesel injection pumps. Fuel filters were being blocked with black sticky gel caused by the use of lubricity additives based on a specific type of divalent acid.⁵¹

The literature indicates that treat rates typically vary from 20 to 200 mg/L. Higher concentrations are occasionally used, although in general, benefits appear to decrease at concentrations above 500 mg/L. Oxidative corrosion and associated sensitivity to moisture are eliminated by trace quantities of corrosion inhibitor additives. However, these additives have little or no effect on adhesion and scuffing wear mechanisms. While corrosion and rust inhibitor

additives are commonly blended to distillate fuels at 10-15 ppm by the petroleum producers to protect transport pipelines, this low concentration provides little protection to consumers because of leaching during transportation and handling.

Stanadyne, the National Biodiesel Board, and West Central Soy, in comments to the proposal, indicate that blending biodiesel with low lubricity conventional diesel fuel can increase the lubricity to acceptable levels. Biodiesel is a zero sulfur diesel fuel made from domestically produced renewable fats and oils. Testing of biodiesel at Stanadyne indicated that the blending of two percent biodiesel with any conventional diesel fuel will be sufficient to address the lubricity concerns that we have with existing diesel fuels. However, more testing would be required to determine the required level of biodiesel in fuels not yet being produced, such as the 15 ppm sulfur fuel required by today's action. Stanadyne indicates the inclusion of low blends of biodiesel is desirable for two reasons. First, it would eliminate the inherent variability associated with the use of other additives, and would also eliminate the question of whether sufficient additive was used. Second, biodiesel is a fuel or a fuel component rather than an additive. It is possible to burn pure biodiesel in conventional diesel engines. Thus, if more biodiesel is added than required for adequate lubricity, there will not be any adverse consequences that might be seen if other lubricity additives are used at too high a level.

Also, it is possible for equipment producers to design new injection system equipment to tolerate lower lubricity fuels. Revised manufacturing practices to include improved materials successfully allowed commercial aircraft to operate continuously with very poor lubricity kerosene-based fuels. Studies sponsored by the U.S. Army also confirmed the possibility of reducing or eliminating the effects of poor lubricity through the use of improved metallurgy. This approach could be applied to fuel systems for commercial compression ignition engines. Conversion kits are already available to allow many pump systems to operate on low-lubricity/low viscosity fuels and are commonly used on engines in Arctic regions. For the purposes of this rule, we will assume that such conversions will not be commonplace in the commercial vehicle and vehicle engine market.

Recommendations by the commentors were largely split by industry and are briefly summarized here. They are discussed in more detail in the Response to Comments document in the public docket. The equipment manufacturers indicated that the "voluntary" approach is not adequate today, and is not likely to be adequate with the 15 ppm sulfur standard. For example, Stanadyne (and DOD) indicated that their experience with the current policy of treating fuel on an as-needed basis has fallen far short of ensuring good fuel lubricity and that a voluntary approach under the 15 ppm sulfur program will lead to wide scale lubricity problems. EMA, Cummins, the Alliance of Automobile Manufacturers and Stanadyne recommended that we specify lubricity measurement methods and set limits. DOD recommended that EPA stress to the industry the importance of having the appropriate performance requirements in the ASTM specification and to encourage the industry to develop standards by imposing a deadline for industry-wide implementation.

API, Marathon Ashland Petroleum, the American Trucking Association and Cenex Harvest States Cooperatives also expressed concern about the impact of today's action on lubricity and recommended that EPA fully explore the lubricity issue; but API and Marathon Asland Petroleum also commented that regulating lubricity is not necessary. Stanadyne and the National Biodiesel Board suggested that we could require biodiesel to be blended with the 15 ppm sulfur diesel fuel, thereby alleviating lubricity concerns otherwise apparent with the low sulfur diesel fuel. By doing so, there would be no need for us to adopt a voluntary or minimum lubricity standard.

5. Today's Action on Lubricity: A Voluntary Approach

We have decided not to establish a lubricity standard in today's action. We believe the best approach is to allow the industry and the market to address the lubricity issue in the most economical manner, avoiding an additional regulatory scheme. A voluntary approach should provide adequate customer protection from engine failures due to low lubricity, while providing the maximum flexibility for the industry. This approach will be a continuation of current industry practices for diesel fuel produced to meet the current Federal and California 500 ppm sulfur diesel fuel specifications, and benefits from the considerable experience gained since 1993. It recognizes the uncertainties of testing and measuring fuel for lubricity, and will also include any new specifications and test procedures that we expect will be adopted by the American Society for Testing and Materials (ASTM) regarding lubricity of highway diesel fuel quality. We fully expect the refining industry, engine manufacturers and end users to work together to resolve any issues as part of their normal process in dealing with customer and supplier fuel quality issues.

We do not believe that an EPA regulation is appropriate for several reasons. First, the expertise and mechanism for a lubricity standard already exist in the industry. According to the comments, the industry has been working on a lubricity specification for ASTM D-975, and low cost remedies for poor lubricity have already been proven and are already being used around the world. Although some commenters expressed concerns that the ASTM process might move too slowly to establish a lubricity specification by 2006, we fully expect that today's action will increase the urgency of those working to establish an ASTM D-975 lubricity specification, and we believe they will do so in time for the production and distribution of the low sulfur highway diesel fuel. We will do our part to encourage the ASTM process be brought to a successful conclusion.

Second, we have no firm basis to justify a lubricity specification in today's action. One such basis might be adequate demonstration that a lubricity level below or above a certain specification would either cause emissions to increase, or hinder the operation of emission control equipment. However, we have no evidence that lubricity impacts emissions, or emission control equipment. This issue is primarily a concern about equipment performance. Equipment

performance is more appropriately addressed by the industry rather than government regulation by this Agency.

Third, even if we had a statutory basis to justify a lubricity standard, we are concerned that establishing an EPA lubricity regulation would provoke the same disagreements that the industry is now engaged in its efforts to establish an ASTM D-975 specification. We are in no better position to judge those issues than the industry experts who are already involved. Further, once a specification is put into the regulations and the industry subsequently determines that the specification should be changed, based on new information or circumstances, the burden would be on us to amend the mandated specification by rulemaking. This is a significant burden to put on the Agency for an engine performance issue that can and should be resolved by the industry without government intervention.

6. Are There Concerns Regarding the Impact of Diesel Desulfurization on Other Fuel Properties?

EPA is not taking action today on any fuel properties other than sulfur. We have examined the impact of fuel properties other than sulfur, such as aromatics, on the materials used in engines and fuel supply systems. We do not believe there will be impacts on materials from such other fuel properties.

While there were some problems with leaks from fuel pump O-ring seals made of a certain material (Nitrile) after the introduction of 500 ppm sulfur diesel fuel in 1993, these issues have since been addressed by equipment manufacturers who switched to materials that are compatible with low aromatic fuels. The leakage from the Nitrile seals was determined to be due to low aromatic levels in some 500 ppm fuel, not the low sulfur levels. In the process of lowering the sulfur content of some fuel, some of the aromatics had been removed. Normally, the aromatics in the fuel penetrate the Nitrile material and cause it to swell, thereby providing a seal with the throttle shaft. When low aromatic fuel is used after conventional fuel has been used, the aromatics already in the swelled O-ring will leach out into the low aromatics fuel. Consequently, the Nitrile O-ring will shrink and pull away, thus causing leaks, or the stress on the O-ring during the leaching process causes it to crack and leak. Not all off highway fuels will cause this problem, because of the amount and type of aromatics will vary. Subsequently, one engine manufacturer recommended replacement of the old O-ring seals in leaking fuel pumps with a new part of the same material, reasoning that the new part is not worn or has not taken a compression set. One fuel producer recommended switching all fuel injection pump applications to a different material (Viton) . Fuel pumps using a Viton material for the seals did not experience leakage.

In comments to the proposal, the EMA, American Trucking Association, API and Marathon Ashland Petroleum expressed general concerns about potential impact of 15 ppm

sulfur diesel fuel on elastomer compatibility. However, these comments did not suggest that the 15 ppm sulfur diesel fuel will likely cause elastomer compatibility problems, or that any preemptive action by EPA or the industry is necessary. EMA clarified that the elastomer compatibility difficulties in the early days of the 500 ppm sulfur fuel program were likely a result of severe aromatic reductions in some of the fuels, not necessarily the removal of sulfur. We have no reason to believe that additional problems will occur with a change of fuel from 500 to 15 ppm sulfur.

D. Feasibility of Maintaining Off highway Fuel in the Distribution System

1. Overview

There are a number of potential links in the highway diesel fuel distribution system from the source of the fuel (refinery or importer) to the fuel retailer or fleet operator (hereafter referred to as the point-of-use).ⁿ Depending on the location of the point-of-use relative to the fuel source, the path of any given batch of highway diesel fuel through the system can include various combinations of these links. Some highway diesel fuel is transported directly from the refinery rack to the point-of-use via tank truck. However, most fuel is transported via the pipeline system to product terminals. From the storage tanks at such terminal facilities, fuel can either be trucked to the point-of-use or transferred by tank truck to bulk plants for later transfer to the point-of-use.

In some circumstances, highway diesel fuel is also transported to a terminal (or to a pipeline connection) by barge or marine tanker, such as along the eastern seaboard, from Texas to Florida, and in the case of imports. In cases where pipeline service is limited, fuel is also shipped to the terminal by rail car. Smaller tank trucks called tank wagons are used to deliver fuel to a variety of users including smaller retailers, fleet operators, and heating oil customers. Tank wagons normally have multiple tank compartments to accommodate the delivery of several different fuel types in a single delivery circuit. Most tank wagons also have a separate delivery system for each product. There is a trend towards the increased use of such separate delivery systems.

The same facilities in the fuel distribution system that are used to handle highway diesel fuel are sometimes used to handle other products, including those with a high sulfur content. As a result, there is currently some mixing of high sulfur products into highway diesel fuel. Sulfur contamination of highway diesel fuel from such mixing can occur at each link in the distribution

ⁿ For additional discussion of the make-up of the highway diesel fuel distribution system, please refer to the National Petroleum Council's (NPC) report on U.S. Petroleum Refining (attachment #6 in docket item IV-D-343) and to the Draft RIA for the proposed rule.

system and is cumulative. Therefore, fuel batches whose distribution paths contain more links are subject to more instances where contamination can occur.

The pipeline system is the primary source of potential mixing of high sulfur products with highway diesel fuel in the distribution system. Transport by pipeline can involve a number of steps. For example, fuel is placed in storage tanks prior to injection into the pipeline and at transfer points between a main pipeline and branch lines or another operators pipeline. Thus, there are a number of instances when highway diesel fuel can come into contact with high sulfur products during shipment by pipeline. Pipeline systems vary greatly in the factors that can contribute to product mixing. These factors include in the pipeline diameter, length, flow rate, and number of branches off the main pipeline line. The Association of Oil Pipelines (AOPL) stated that as the complexity of the pipeline system increases, there are a greater number of potential sources of sulfur contamination.⁵²

The most significant opportunity for mixing of high sulfur products into highway diesel fuel during shipment by pipeline is associated with the fact that different products are normally shipped through the same line sequentially with no physical separation between the products. The mixture between two products where they abut each other in the pipeline is referred to as interface when it can be blended into another product, and transmix when it must be returned to the refinery for reprocessing. Pipeline operators take care to sequence the different products they carry in such a way as to minimize the amount of transmix generated and the cost of downgrading interface volumes to a lower value product.

Smaller batches of highway diesel fuel are commonly drawn off from a larger batch at various points as it travels along the length of a main pipeline. A batch of fuel can also be injected into a pipeline at various points along its length. An additional volume of interface can be generated during each of these transfers. To minimize the generation of additional interface volumes, such transfers are accomplished within the “heart”^o the batch already in the pipeline whenever possible. Additional interface volumes can also be generated when a batch of fuel is passed between different pipeline systems. This is primarily due to the need for the fuel batch to be temporally placed in a stationary storage tank to facilitate the transfer between pipeline systems.

All of the product that must be downgraded to a lower value product because of mixing in the pipeline is sometimes referred to as interface, although strictly speaking, interface is only generated when two products abut each other in the pipeline. Relatively small volumes of mixed products are commonly included in the statement of total interface volume, such as those associated with purging products contained in the manifolds at tank farms and in preparing for

^o The heart of a batch of fuel in a pipeline is that portion far enough from either end of the batch to ensure that no mixing occurs with other adjacent products.

the injection of a batch of fuel into the pipeline. The various concerns related to potential sulfur contamination during the distribution of highway diesel fuel by pipeline are discussed in the following section on limiting contamination in the pipeline system.

There are also significant concerns specific to limiting sulfur contamination in the other links in the distribution system (terminals / bulk plants, tank trucks / tank wagons, marine transport). These concerns include the potential for contamination of 15 ppm highway diesel fuel when it is put into a stationary storage tank, vehicle tank compartment, transfer line, or delivery line that previously held high sulfur products. Sulfur contamination can also result from leaking valves. Diesel fuel sulfur content can also be impacted by the use of additives that have a high sulfur content. These concerns are discussed in separate subsections that follow on limiting contamination at stationary storage facilities, during transport by surface vehicles, during marine transport, and from diesel fuel additives. Issues related to limiting contamination at tank farms, whether they are part of a pipeline operation or a terminal facility, are discussed in the section on limiting contamination at stationary storage facilities.

The extent to which mixing of high sulfur products into highway diesel fuel can be tolerated is dependent on the maximum allowable sulfur content for highway diesel fuel, the sulfur level of highway diesel fuel as it leaves the refinery gate, and the sulfur content of the product with the highest sulfur cap that shares the distribution system with highway diesel fuel. The highest sulfur product that presents a concern with respect sulfur contamination of highway diesel fuel from mixing in the distribution system is off highway diesel fuel, which has an industry-standard maximum sulfur content of 5,000 ppm and often averages approximately 3,000 ppm sulfur. EPA's current cap on the sulfur content of highway diesel fuel is 500 ppm with actual sulfur level at production averaging approximately 340 ppm.^p Thus, currently there is a 1 to 10 ratio of the maximum allowable sulfur content of highway diesel fuel to the highest sulfur content of other products in the distribution system. This ratio provides a reference regarding the current experience of the distribution industry in limiting the sulfur contamination of highway diesel fuel.

Another useful reference is provided by the ratio of the of the difference between actual highway diesel fuel sulfur levels and the 500 ppm cap to a reasonably severe sulfur level in off highway diesel fuel. The average sulfur level of current highway diesel fuel is 160 ppm below the 500 ppm cap. This difference below the sulfur cap is hereafter referred to as the "headroom" below the cap. Although the maximum sulfur level of of highway diesel fuel potentially is 5,000 ppm, fuel batches near this cap are likely to be very rare and to originate only from a very limited number of refineries. In addition, batches of of highway diesel fuel that are near the 5000 sulfur cap are likely to be diluted with batches of lower sulfur content before (or as) they are introduced in the pipeline. Based on this, we believe that 4,000 ppm is an appropriately severe sulfur level

^p See section IV.A.2. regarding current sulfur levels in highway diesel fuel.

to compare against the current headroom below the existing sulfur cap for highway diesel fuel. Thus, currently there is a 1 to 25 ratio of the current headroom below the highway diesel fuel sulfur standard to the highest sulfur level in a product that highway diesel fuel might reasonably be expected to come into contact with in the distribution system.

When the 15 ppm sulfur cap for highway diesel fuel is implemented, of highway diesel fuel could have a sulfur content of approximately 333 times the highway diesel fuel sulfur cap. Under our sulfur program, we expect that highway diesel fuel designated as meeting the 15 ppm cap on sulfur content will leave the refinery with an average sulfur concentration of approximately 7 ppm. Consequently, for highway diesel fuel to comply with the 15 ppm sulfur standard, sulfur contamination could contribute no more than 5 - 8 ppm to the final sulfur of the fuel. This translates to a 1/500 - 1/800 ratio of the maximum allowable sulfur contamination in highway diesel fuel to the highest sulfur level in a product that highway diesel fuel might reasonably be expected to come into contact with in the distribution system.

Based on a comparison of the above ratios, batches of highway diesel fuel meeting a 15 ppm sulfur cap will be able to tolerate much less mixing with high sulfur products than can current batches of 500 ppm highway diesel fuel. It follows that adequately limiting sulfur contamination during the distribution of highway diesel fuel meeting a 15 ppm sulfur cap may be significantly more challenging than under the current 500 ppm sulfur cap. A comparison with instances where the distribution industry has managed other difficult contamination issues is useful in evaluating the relative magnitude of the new challenge posed by the implementation of a 15 ppm cap on the sulfur content of highway diesel fuel.

In Sweden, diesel fuel meeting a 10 ppm sulfur cap has been distributed for some time. However, high sulfur fuel oils are typically distributed in a separate distribution system in Sweden. Due to this separation, Swedish 10 ppm sulfur diesel fuel is mostly segregated from high sulfur products. Therefore, it is difficult to draw inferences from the Swedish experience on how well the U.S. distribution system will accommodate 15 ppm highway diesel fuel. ARCO Petroleum currently markets highway diesel fuel meeting a 15 ppm cap in a limited fashion in California. However, this effort has yet to expand to the extent that their product is shipped in the common distribution system. Thus, current experience of marketing 15 ppm diesel fuel in the U.S. does not provide a useful reference with respect to the conditions when our sulfur program will be implemented.

The distribution system has experience in limiting contamination of other products it handles that may provide techniques useful in adequately controlling the sulfur contamination of 15 ppm sulfur highway diesel fuel. For example, the presence of small quantities of gasoline in

diesel fuel can cause the industry standard flash point for diesel fuel to be exceeded.⁹ This is a significant concern because diesel fuel with an inappropriately high flash point presents a explosion hazard and its use can result in driveability problems.⁷ In addition, it is very difficult for a batch of diesel fuel that is out of compliance with the flash specification to be brought back into compliance by blending in a quantity of compliant diesel fuel into the noncompliant batch.⁸ Consequently, extreme care is taken to prevent mixing gasoline into diesel fuel. One relevant example is that in separating a batch of diesel fuel from a batch of gasoline that it abuts in the pipeline, none of the interface is allowed into the batch of diesel fuel.

Although most of the fuels handled in the distribution system are fungible, some segregated products are carried such as high cetane diesel fuel and Amoco's clear premium gasoline. In the case of Amoco's clear gasoline, mixing with other products must be strictly limited to maintain the clarity of the product. This product is routinely transported by pipeline. Limiting contamination during the transportation of such specialty products involves unique challenges that may provide techniques useful in limiting sulfur contamination of 15 ppm highway diesel fuel.

The current experience with limiting dye contamination in highway diesel fuel provides another useful point of reference regarding a contamination concern that is currently being managed by the distribution system. EPA requires that highway diesel fuel must show no trace of the red dye which is required to be present in of highway diesel fuel by the Internal Revenue Service (IRS) to demonstrate its non-tax status. A very small quantity of dyed of highway diesel fuel mixed into highway diesel fuel can cause in a visible trace, resulting in a violation of EPA requirements. To satisfy IRS requirements at the terminal, red dye must be present in of highway diesel fuel at a concentration of at least 3.9 pounds per 1000 barrels (approximately 13 ppm).⁵³ Some pipeline operators commonly add a lesser amount of dye upstream in the pipeline. One operator requires that 0.75 mg per liter or approximately 0.9 ppm is added to of highway diesel fuel prior to its injection into the pipeline. This practice is followed to minimize the loss of red dye during transportation of dyed fuel and to reduce the risk of contaminating highway diesel fuel with red dye in the pipeline system. An additional quantity of dye is then added at the terminal to meet IRS requirements. Approximately 0.1 mg per liter of red dye in diesel fuel is sufficient to result in a visible trace. This translates to a ratio of 1 to 130 regarding the maximum amount of dye contamination that can be tolerated in highway diesel fuel to the minimum

⁹ The impact of mixing gasoline into diesel fuel on diesel flash point is a function of the high vapor pressure of gasoline relative to diesel fuel. In a diesel storage tank, gasoline contained in the diesel fuel will contribute a disproportionate fraction of the total fuel volume that is in the vapor phase. During the winter, this contribution can cause the vapor phase in a storage tank to be combustible, resulting in an explosion hazard.

⁷ Driveability problems can result from premature ignition of the fuel-air charge in the cylinder.

⁸ This procedure is the preferred method of handling noncompliant fuel batches.

concentration of red dye that must be in of highway diesel fuel to meet IRS requirements (3.9 pounds / 1000 barrels).

Since no red dye is intentionally added to highway diesel fuel, any dye that is present must originate from contamination from of highway diesel fuel. This suggests that it may be most appropriate to base a comparison of the experience in limiting dye contamination with the difficulty in limiting sulfur contamination under our program on the 1/500 - 1/800 ratio of the maximum amount of sulfur contamination that we expect could be tolerated in 15 ppm highway diesel to the highest sulfur level in a product that highway diesel fuel might reasonably be expected to come into contact with in the distribution system.

The fact that red dye is not added at the full concentration required by the IRS until after off highway diesel fuel reaches the terminal, prevents a direct comparison of the experience in limiting dye contamination with that of limiting sulfur contamination of highway diesel fuel meeting a 15 ppm sulfur cap during transport by pipeline. However, the 1/130 ratio of the concentration of dye allowed in highway diesel fuel to the minimum concentration required in of highway diesel fuel does provide a useful reference regarding a the current ability of distributors downstream of the terminal (such as tank truck and tank wagon operators) to limit contamination.

The IRS can impose a more stringent chemical test to detect red dye in highway diesel fuel at levels which do not cause a visible trace. A violation of IRS requirements can be established based on the results of such a test. While we do not have information on the concentration of red dye that could be detected by such a test, it is reasonable to assume that it would be substantially lower than 0.1 mg per liter (which causes a visible trace). Therefore, the ratio of the maximum concentration of dye allowed in highway diesel fuel to the minimum concentration required in of highway diesel may be considerably closer to the 1/500 - 1/800 ratio associated with limiting sulfur contamination of highway diesel fuel meeting a 15 ppm sulfur cap. If this is the case, it would suggest that distributors downstream from the terminal are currently coping with a level of difficulty in limiting contamination similar to that will be encountered as a result of our sulfur program.

The experience in limiting lead contamination in unleaded gasoline from leaded gasoline during the phase-out of lead in U.S. gasoline provides the most useful point of reference. The lead in leaded gasoline was added fully at the refinery, so a comparison of this experience with the difficulty of limiting sulfur contamination under our sulfur program should be valid throughout the entire distribution system. The situations where unleaded gasoline came into contact with leaded gasoline (or traces of leaded gasoline) also parallels the situations that will be encountered regarding the transportation of highway and of highway diesel fuels under our sulfur program. For example, batches of unleaded and leaded gasoline abutted each other during shipment by pipeline, and the same storage tanks and delivery equipment would sometimes be used to handle both types of gasoline. This further supports the applicability of comparing the

experience in limiting lead contamination to that of limiting sulfur contamination under our sulfur program.

The maximum lead concentration in unleaded gasoline has always been 0.05 grams per gallon, with the additional requirement that no lead be intentionally added to unleaded gasoline. The maximum lead concentration in leaded gasoline was reduced in steps. In 1980, EPA adopted a “pool standard” of 0.5 grams lead per gallon. Compliance with this “pool standard” was based on evaluating the lead added to leaded gasoline by a given refiner divided by all of the gasoline that the refiner produced (unleaded and leaded). This standard resulted in typical lead levels in leaded gasoline of approximately 1 gram per gallon. In 1982, EPA adopted a 1.1 gram per gallon “leaded gallons standard”. At this time, approximately 50 percent of the gasoline pool was leaded gasoline. Compliance with this “leaded gallons standard” was based on evaluating the lead added to leaded gasoline by a given refiner divided by the volume of leaded gasoline that the refiner produced. The use of this “leaded-gallons standard” had little effect on the in-use lead concentration in leaded gasoline, which remained at approximately 1 gram / gallon until the standard was reduced to 0.5 grams of lead per gallon of leaded gasoline in 1985.

During the time when the lead content of leaded gasoline was typically 1 gram per gallon (near the maximum allowed concentration), lead levels in unleaded gasoline were typically less than 0.005 gram per gallon. This translates to approximately a 1 to 200 ratio of the typical maximum concentration of lead in unleaded gasoline to the typical maximum lead concentration in lead gasoline. Similar to the discussion above regarding dye contamination, the fact that the lead in unleaded gasoline could only have originated from contamination from leaded gasoline suggests that it is most appropriate to base our comparison with the leaded gasoline experience on the 1/500 - 1/800 ratio of the maximum amount of sulfur contamination that we expect could be tolerated in 15 ppm highway diesel to the highest sulfur level in a product that highway diesel fuel might reasonably be expected to come into contact with in the distribution system.

The various ratios discussed above are summarized in the following table IV.D-1.

Table IV.D-1. Ratios Used in Comparing the Relative Difficulty in Limiting Contamination During the Distribution of Various Fuels

$\frac{500 \text{ ppm Highway Diesel Sulfur Cap}}{5,000 \text{ ppm Off highway Diesel Sulfur Cap}}$	$\frac{500}{5,000}$	$\frac{1}{10}$
$\frac{15 \text{ ppm Highway Diesel Sulfur Cap}}{5,000 \text{ ppm Off Highway Diesel Sulfur Cap}}$	$\frac{15}{5,000}$	$\frac{1}{333}$
$\frac{\text{Current Headroom Under 500 ppm Cap}}{\text{Severe Sulfur Level in Product that Contacts Highway Diesel}}$	$\frac{160}{4,000}$	$\frac{1}{25}$
$\frac{\text{Expected Headroom Under 15 ppm Cap}}{\text{Severe Sulfur Level in Product that Contacts Highway Diesel}}$	$\frac{5 \text{ to } 8}{4,000}$	$\frac{1}{500} \text{ to } \frac{1}{800}$
$\frac{\text{Maximum Dye Concentration in Highway Diesel}}{\text{Required Dye Concentration in Off Highway Diesel}}$	$\frac{0.1 \text{ ppm}}{13 \text{ ppm}}$	$\frac{1}{130}$
$\frac{\text{Typical Maximum Lead Concentration in Unleaded Gasoline}}{\text{Typical Maximum Lead Concentration in Leaded Gasoline}}$	$\frac{0.005 \text{ g/gal}}{1 \text{ g/gal}}$	$\frac{1}{200}$

The Association of Oil Pipelines (AOPL) stated that their members believe the task of preventing sulfur contamination in 15 ppm highway diesel fuel will be more difficult than the transition from leaded to unleaded gasoline, the protection of the flash property of diesel fuel, or the prevention of dye contamination.⁵⁴ Comparing the ratios discussed above regarding limiting dye contamination (1/130) and limiting lead contamination (1/200), with the ratio of the anticipated headroom under the 15 ppm cap for highway diesel fuel to the highest sulfur concentration in off highway diesel fuel (severe level referenced in table IV.D-1) that is likely to contact highway diesel fuel in the distribution system (1/500 - 1/800), suggests that this is the case. However, this comparison also suggests that the challenge of limiting sulfur contamination in highway diesel fuel meeting a 15 ppm sulfur cap is not an order of magnitude different to the challenge of limiting lead contamination in unleaded gasoline that was successfully managed 25 years ago. This suggests that meeting the new challenge can be accomplished by improving upon existing techniques to limit contamination, rather than requiring a paradigm shift in the way highway diesel fuel is distributed.

Not all pipelines, terminals, and other fuel distributors handle off highway diesel fuel. At such facilities, the challenge of limiting sulfur contamination of highway diesel fuel is, and will continue to be, somewhat less difficult than at facilities that handle off highway diesel fuel. This is because other products that might share the same distribution system have a lower maximum sulfur content than off highway diesel fuel. For example, jet fuel and kerosene is subject to an industry-standard sulfur cap of 3,000 ppm. The ratio of the maximum amount of sulfur that will be allowed in highway diesel fuel under our sulfur program to the maximum concentration allowed in jet fuel or kerosene is 1 to 200. This ratio is identical to that associated with limiting lead contamination during the lead phase-down program. This suggests that the difficulty of limiting sulfur contamination during the distribution of 15 ppm highway diesel fuel at facilities that do not handle off highway diesel fuel will be of a similar magnitude to that experienced in limiting lead contamination during the lead phase-down program.

Although not within the scope of current EPA regulations, the difficulty of distributing highway diesel fuel with a 15 ppm sulfur cap would be significantly reduced if the sulfur content of nonoad diesel fuel were reduced by a future rulemaking. If this took place the product with the highest sulfur content shipped by pipeline would be jet fuel or kerosene which have a maximum sulfur content of 3,000 ppm

In the NPRM, we proposed that with relatively minor changes and associated costs, the existing distribution system would be capable of adequately limiting sulfur contamination during the distribution of highway diesel fuel with a 15 ppm sulfur cap. These projected changes included an increase in the amount of highway diesel fuel that must be downgraded to a lower value product in the pipeline system due to changes in interface handling practices, and increased terminal testing for quality control purposes. We also recognized that distributors downstream of the refinery such as tank truck operators would need to more carefully and consistently observe current industry practices to limit contamination, but projected that this could be accomplished at an insignificant cost. We proposed to hold diesel fuel additives to the same sulfur cap that would apply to diesel fuel, and projected that this could be accomplished without causing a significant burden to fuel marketers and additive manufacturers.

We received a number of comments on the proposed rule that substantial uncertainties exist regarding the ability of the distribution system to adequately limit sulfur contamination of highway diesel fuel meeting a 15 ppm sulfur cap. Some commenters stated that the only way to adequately limit sulfur contamination in the distribution of diesel fuel meeting a 15 ppm sulfur cap may be to create a completely segregated system.

Several commenters stated that EPA should conduct testing to further evaluate the ability of the distribution system to limit contamination to the very low levels necessitated by the implementation of a 15 ppm sulfur cap. The Department of Energy (DOE) called on EPA to conduct a comprehensive technology review regarding EPA's sulfur control program in the 2003 time frame, including the feasibility of distributing diesel fuel with a 15 ppm sulfur cap.⁵⁵ DOE

stated that such a review is warranted because the distribution industry has never faced a similar challenge in limiting contamination and would need to take extraordinary actions to do so. DOE suggested that EPA participate in an experimental shipment of highway diesel fuel meeting a 15 ppm sulfur cap to evaluate the difficulties faced in limiting contamination.

While we acknowledge that today's rule will pose a substantial new challenge to the distribution system, we believe that the additional measures outlined in this section will sufficiently address issues associated with limiting sulfur contamination during the distribution of 15 ppm sulfur highway diesel fuel. We expect that the changes to distribution practices that may be needed will be logical outgrowths and extensions of current practices. With modest modifications, the existing distribution system will be capable of limiting contamination during the distribution of 15 ppm highway diesel fuel. The changes needed in the distribution system as a result of our sulfur program will be readily apparent once industry focuses on meeting the challenge of limiting sulfur contamination during the distribution of 15 ppm highway diesel fuel. Therefore, testing by EPA or a formal technology review of the ability of the system to limit contamination during the distribution of 15 ppm highway diesel fuel is not necessary.

It is possible that sources of sulfur contamination which did not hitherto represent a significant concern may need to be reevaluated to assess their potential impact on maintaining the 15 ppm cap on the sulfur content of highway diesel fuel. Although all of these potential minute sources of sulfur contamination in the distribution system may not have been identified and quantified, we believe that the total contamination from such sources, while made more significant by the implementation of the 15 ppm sulfur cap, is not of a sufficient magnitude to jeopardize the feasibility of distributing 15 ppm sulfur highway diesel fuel.

We anticipate that the distribution system will conduct an evaluation of the potential sources of contamination to ensure that each segment in the system has a satisfactory margin of compliance below the 15 ppm cap. As a result of this evaluation, we anticipate that industry may take measures to help adequately limit sulfur contamination in addition to those specifically identified at this time. However, we anticipate that these measures will be the exception rather than the rule. We do not anticipate that such additional measures will result in an unacceptable burden to the fuel distribution industry (see Section V.C.3.).

We anticipate that the distribution industry will resolve what minor issues that might remain while gearing up for the implementation of our sulfur program. We also anticipate that some refiners will begin producing 15 ppm diesel fuel well before the time they are required to do so. The voluntary efforts currently under way to market 15 ppm diesel are also expected to expand in the years before the implementation of our sulfur control program. This will facilitate the evaluation by the distribution system of their ability to limit sulfur contamination, and help to ensure that whatever additional changes that may be necessary are made before industry is faced with a regulatory compliance requirement. Industry will also gain experience in limiting sulfur contamination in complying with the recently finalized Tier 2 gasoline sulfur requirements.

Some commenters on the NPRM stated that tanks that handle highway diesel fuel meeting a 15 ppm cap would need to be dedicated to that purpose, necessitating the construction of a substantial number of storage tanks, tank trucks, tank wagons, and barges at unacceptably high cost and with impacts on numerous small businesses. We do not believe that our sulfur control program will cause a significant increase in the extent to which highway diesel fuel must be segregated from high sulfur products in the distribution system beyond the segregation that already exists in much of the system today. Many of the stationary storage tanks, tank trucks, tank compartments and delivery systems on tank wagons, and tank compartments on barges which are used to handle highway diesel fuel are already dedicated to this purpose. Further, we understand that there is a trend to increase this level of dedication, at least among large companies in the distribution industry. Although our program may encourage this trend, we believe that situations where our program will require equipment to be dedicated to handling highway diesel fuel will be the exception rather than the rule.

Fuel distributors commented that contamination during the distribution of fuel in tank trucks, tank wagons, barges, and rail cars could not be successfully managed simply by careful and consistent observation of current industry practices, as we asserted in the NPRM. As discussed below, we continue to believe that in most cases current industry practices will be sufficient to limit contamination if properly followed. The one exception is in the case of barges, which may need additional flushing when switching from a high sulfur product to 15 ppm highway diesel fuel (see Section IV.D.4.).

Several commenters on the NPRM stated that unavoidable contamination could cause many batches of highway diesel fuel to be noncompliant with the 15 ppm cap, resulting in shortages and high costs. These commenters also stated that the current practice of diluting batches of highway diesel fuel that do not comply with sulfur requirements with batches of fuel that have a sulfur content below the standard to bring the resultant mixture into compliance with the sulfur specification would no longer be possible when a 15 ppm cap on the sulfur content of highway diesel fuel was implemented. They related that batches of highway diesel fuel that were found to be noncompliant with the 15 ppm sulfur cap would need to be shipped by truck back to the refinery for reprocessing (treated as transmix), resulting in substantial disruption the market and cost. The Association of Oil Pipelines stated that pipeline operators may need to change the products they choose to place in the pipeline adjacent to batches of highway diesel fuel meeting a 15 ppm cap.⁵⁶ If this were the case, additional volumes of transmix could be generated.

We believe that an insignificant additional volume of transmix will be generated as a result of our sulfur program. The generation of such additional transmix volumes will be limited to circumstances related to the transfer of products through the manifolds at stationary storage facilities and in preparing for the injection of products into the pipeline (line fill). We expect that no changes will be needed in the choice of products that abut highway diesel fuel in the pipeline. Therefore, we believe that no significant additional volume of transmix associated with pipeline interface will be generated as a result of our program.

We believe that there will not be a significant increase in the volume of highway diesel fuel discovered to exceed the sulfur standard downstream of the refinery as a result of our sulfur program. Distributors will quickly optimize the distribution system using the means described in this section to avoid creating additional volumes of out of specification product. We anticipate that the preferred method of coping with batches of highway diesel fuel that are discovered to exceed the 15 ppm sulfur cap will continue to be to blend them back into compliance whenever possible. We expect that only in the infrequent instances where other options do not exist, will batches that exceed the 15 ppm cap need to be returned to the refinery for reprocessing (see Section IV.D.6). We believe that such rare circumstances will not significantly increase the difficulty (and cost) of handling out-of specification highway diesel batches under our sulfur program.

We received comments that we had underestimated the amount of highway diesel fuel that would need to be downgraded to a lower value product. Commenters stated that the amount could be so large as to contribute to difficulties in supplying sufficient quantities of highway diesel fuel.

In response to comments, we adjusted our estimate of the amount of highway diesel fuel that would need to be downgraded to a lower value product. Our analysis indicates that the magnitude of the additional volume that would need to be downgraded can be accommodated without causing supply problems or other disruptions to the market (see Section IV.A.9.).

Additive manufacturers stated that holding additives to a 15 ppm cap would result in a significant burden to additive manufacturers due to the need to reformulate their additive packages. They also stated that for certain essential types of diesel additives, no low sulfur alternatives exist.

Our analysis of the Fuel and Fuel Additive (F&FA) database indicates that additives with a sulfur content below 15 ppm are available to meet every purpose in use. However, we agree with commenters that the contribution of high sulfur additives can be adequately controlled without holding such additives to a 15 ppm sulfur cap. Therefore, we included a provision to allow the continued use of additives that exceed a sulfur content of 15 ppm provided that this does not cause the 15 ppm cap on the sulfur content of highway diesel fuel to be exceeded. This provision will prevent any significant impacts from our sulfur program related to the use of diesel fuel additives. Although our sulfur program may encourage high sulfur additives to be retired from the market, we have structured the program in a way that will not require this to happen.

A number of commenters stated that difficulties in complying with our sulfur program would be eased substantially if EPA were to include a downstream tolerance on the 15 ppm sulfur standard to reflect measurement variability. In response to comments, we incorporated a downstream tolerance on the 15 ppm sulfur standard in the compliance provisions of our program to accommodate measurement variability. As suggested in the comments, we believe

this will substantially ameliorate concerns regarding the ability to comply with the 15 ppm sulfur standard downstream of the refinery. We believe this allowance will not significantly impact the average level of fuel sulfur in-use. Therefore, providing this measurement tolerance will not significantly reduce the emissions benefits of our program.

We concluded that despite the heightened challenge to the distribution industry caused by our sulfur program, it will be feasible to distribute 15 ppm highway diesel fuel with relatively minor modifications to the existing system which can be accomplished at modest additional costs. The potential sources of sulfur contamination and the additional measures that we anticipate will need to be taken to limit such contamination are discussed in the following sections. Areas where further changes may be found to be called for as a result of the anticipated process of optimizing the distribution system to limit sulfur contamination are also discussed below. Please refer to Section V.C. on the costs to the distribution system, and to the Response to Comments (RTC) document for our reply to comments on the feasibility of distributing highway diesel fuel under our sulfur program.

2. Feasibility of Limiting Sulfur Contamination in the Pipeline System

The primary source of potential sulfur contamination in the pipeline system is associated with the handling practices for interface volumes associated with shipments of highway diesel. The Association of Oil Pipelines (AOPL) stated that other potential sources of sulfur contamination include pipeline dead legs, line fill, tank heels, tank manifolds, and the fact that some valves designed to facilitate batch changes take as long as 45 seconds or more to close.⁵⁷ There may also be a heightened level of concern regarding leaking valves. AOPL also expressed concern that their current physical methods¹ of evaluating when to make a cut between adjacent batches in the pipeline may not be adequate for determining when a cut should be made between a batch of 15 ppm diesel fuel and another product batch adjacent to it in the pipeline. The Department of Energy (DOE) stated that sulfur contamination from internal surface accumulation of high sulfur product along the sides of pipes and within tanks, which currently is considered negligible, might become significant given the small amount of contamination that could be tolerated in fuel that must meet a 15 ppm sulfur cap.⁵⁸

Each potential source of contamination in the pipeline system is discussed in turn below. Some of the concerns discussed in this section, such as those related to the interface handling practices regarding pipeline shipments of highway diesel fuel that abut batches of jet fuel or kerosene, line-fill, and leaking valves are also pertinent to limiting contamination in other parts

¹ Pipeline operators often discern the interface between two products in the distribution system based on a change in fuel density and/or a change in color. Tracking information from upstream in the pipeline is used to help identify the approximate time when the interface between batches will arrive at a given point in the system.

of the distribution system such as terminals and bulk plants. These concerns are discussed here because they are integral facets of the pipeline distribution system.

Pipeline owners operate storage tanks where product is fed into the pipeline, at points along the line where product is exchanged, and at the juncture between two pipelines. These storage tanks are necessary to facilitate the exchange of products in the various lines and to ensure that the pipeline remains in steady operation. Interface and transmix can be generated during this exchange. Concerns related to limiting sulfur contamination in storage tanks used to facilitate pipeline operation are discussed in the section on limiting contamination in stationary storage tanks.

Several commenters stated that our sulfur program would cause a substantial increase the volume of transmix that is generated during the shipment of highway diesel fuel, resulting in an unacceptable burden to industry. This concern is addressed within the sections that address the various potential contamination sources.

a. Interface Handling Practices

i. Current Downgrade Volume

Some pipeline operators currently cut as much as 25 percent of the interface volume generated during the shipment of highway diesel fuel into the highway diesel batch. The other 75 percent of the interface volume is cut into the high sulfur product which abuts the batch of highway diesel fuel in the pipeline. This practice is currently possible because of the large over-compliance with the current 500 ppm standard by refiners.^u By allowing some high sulfur product to mix with highway diesel fuel, the amount of highway diesel fuel that is downgraded to a lower value product is reduced, thereby minimizing cost.

In addition to the amount of interface that is generated during the actual transport of fuel through the pipeline, relatively minor volumes of interface are also generated during the transfer of products into and out of storage tanks associated with pipeline (and terminal) operation, and in preparing to inject a batch of fuel into the pipeline. Given the small diameter of the piping that connects storage tanks and is used to “lay down” a batch of fuel prior to injection into the pipeline relative to the diameter of the pipeline, and the short length of such lines compared to

^u Highway diesel fuel sulfur levels currently average 340 ppm in the United States outside of California. California has its own requirements on highway diesel fuel sulfur content which result in an average sulfur content of 140 ppm within the State of California. See section IV.A.3.

length of pipelines, the amount of interface generated during such product transfers is relatively small compared to that generated in the pipeline.^v

The Association of Oil Pipelines (AOPL) related that the current downgrade accounting system does not provide a ready means to estimate the current volume of highway diesel fuel downgrade.⁵⁹ AOPL stated that this raises concerns regarding the accuracy of the estimates of current downgrade provided by their members and cautioned against their use in estimating the economic impact of our sulfur program. They also stated that the diversity in the characteristics of their members operations led to a wide range in the estimates of the current downgrade volume (ranging from 0.2 percent to 10.2 percent of the total volume of low sulfur diesel fuel shipped by pipeline). These estimates included all of the sources of downgraded highway diesel fuel.

It is worth noting that some commenters on the proposed rule apparently used the upper bound in this range of individual estimates and the assumption that downgrade volumes would double under our program to estimate that 20 percent of 15 ppm highway diesel fuel supplied would need to be downgraded to a lower value product due to mixing with high sulfur products in the distribution system. This approach substantially overestimates the additional highway diesel fuel that would need to be downgraded to a lower value product as a result of our sulfur program because it assumes that the worst case condition with respect to the current downgrade volume is applicable for the entire range of pipeline operators. This does not take into account the diversity in the characteristics of pipeline owner's operations that AOPL related was linked to the wide range in the estimates of the current downgrade volumes that they received from their members.

We believe that the estimates provided by AOPL members provides an adequate characterization of the range of current downgrade volumes across the diverse pipeline distribution system. To derive an estimate of the average downgrade for the pipeline system as a whole today, we used the range of downgrade estimates from AOPL and a characterization of the pipeline distribution system in terms of pipeline diameter and length derived from the PennWell^w pipeline database. Due to the characteristics of fluids as they travel through a pipeline, the larger the pipeline diameter and the longer a batch of product is pumped through a pipeline, the greater degree of mixing with adjacent batches that will take place. Furthermore, larger diameter pipelines tend to be relatively more complex than smaller diameter lines (i.e. have more tank

^v The amount of interface generated is dependent on a number of factors, most prominent of which are the diameter and length of the line through which the product flows. Issues related to "line fill" are specifically discussed in a later section.

^w A proprietary database of information on pipeline and terminal facilities in the United States produced by PennWell MAPsearch Inc., P.O. Box 5237, Durango Colorado, mapsearch.com.

farms and connections to other lines) leading to a larger number of interface volumes being generated for any given batch of fuel as it travels to its ultimate destination.

We assigned a specific estimate of percent downgrade from those provided by AOPL members to each pipeline diameter included in the PennWell database, ranging from 10.2 percent for the largest diameter pipeline to 0.2 percent for the smallest diameter line. In doing so, we assumed that downgrade increases linearly with the cross sectional area of the pipeline. To account for the impact of pipeline length on downgrade volume, we weighted the downgrade estimate for each pipeline diameter by the fraction of total pipeline system length represented by that diameter. By this method, we estimated that the average downgrade for the pipeline system as a whole currently is approximately 2.5 percent of the highway diesel fuel shipped by pipeline.

Data from the Energy Information Administration (EIA) indicates that 85 percent of all highway diesel fuel supplied in the U.S. is sold for resale. Therefore, we believe it is reasonable to assume that only this 85 percent is shipped by pipeline, with the remaining 15 percent being sold directly from the refiner rack or through other means that does not necessitate the use of the common fuel distribution system. By multiplying 2.5 percent by 0.85 we arrived at an estimate of the current amount of highway diesel fuel that is downgraded today to a lower value product of 2.2 percent of the total volume of highway diesel fuel supplied.

ii. Downgrade Volume with 15 ppm Sulfur Standard for Highway Diesel Fuel

We are assuming that when the 15 ppm cap on highway diesel fuel sulfur content is implemented, it will no longer be possible to cut any of the interface volume into highway diesel fuel. This is referred to as a protective interface cut, and corresponds to a doubling of the volume of highway diesel interface volume downgraded to a lower value product compared to the 25 percent / 75 percent cut described above. Some individual AOPL members stated that a protective interface cut would be necessary to limit sulfur contamination during the shipment of 15 ppm highway diesel fuel. Some AOPL members also stated that the amount of highway diesel fuel that would need to be downgraded to a lower value product would likely double as a result of our sulfur program. However, they cautioned that actual losses may be higher depending on the extent to which sulfur from preceding batch trails back into a batch of 15 ppm fuel.

Some pipeline operators currently make a protective interface cut when separating a batch of highway diesel fuel from other products which it abuts in the pipeline. This suggests that our assumption that the amount of highway diesel fuel downgraded to a lower value product will double as a result of the implementation of the 15 ppm cap on the sulfur content of highway diesel fuel will yield a conservatively high estimate of our program's impact. However, given the uncertainties regarding the various sources of highway diesel fuel that must be downgraded to a lower value product, we believe that the use of this assumption provides an appropriate level of

confidence that we are not underestimating the impact of our sulfur program. This estimate is also in agreement with that provided by several commenters.

We believe that it is highly unlikely that any difference that might exist in the physical properties of 15 ppm diesel fuel (e.g. density, viscosity) versus those of current highway diesel fuel will cause a substantial change in the extent to which sulfur from preceding batches trails back into batches of highway diesel fuel. Regardless, our estimate that downgrade volumes will double will help to account for various unknowns that may cause downgrade volumes to increase.

By applying the assumption that highway diesel fuel volumes will double as a result of our sulfur program to the estimate of the current downgrade volume (2.2 percent of highway diesel fuel supplied) we estimated that an additional 2.2 percent of the highway diesel supplied will need to be downgraded to a lower value product to adequately limit sulfur contamination as a result of the implementation of the 15 ppm sulfur standard under our program. In gaining experience with the distribution of 15 ppm highway diesel fuel, we anticipate the pipeline operators may cut a somewhat greater portion of highway diesel fuel batches into products that they abut in the pipeline in order to ensure that no volume of interface is cut into the highway diesel fuel batch. This may result in somewhat more highway diesel fuel being downgraded until pipeline operators become more confident in their ability to make a protective interface cut. However, we do not expect that the additional volumes will be significant and believe that pipeline operators will quickly optimize their interface handling practices to limit the volume of highway diesel fuel that must be downgraded. We anticipate that the expansion of voluntary efforts to market 15 ppm diesel fuel will facilitate such fine tuning of the pipeline system to handle 15 ppm highway diesel fuel prior to the implementation of our sulfur program. We attributed costs for this optimization process in our cost analysis (see section V.C.3).

iii. Changes to the Interface Handling Practices when Highway Diesel Fuel Abuts Shipments of Jet Fuel or Kerosene

The industry specification for the end boiling point of kerosene and jet fuel is much lower than the specification for the end boiling point of diesel fuel. Since the measured end boiling point of a fuel is much more related to the presence of high boiling point fuel species rather than their concentration, a small quantity of diesel fuel mixed into kerosene or jet fuel can cause the end boiling point specification for these products to be exceeded. The current practice when a batch of highway diesel fuel abuts a batch of jet fuel or kerosene in the pipeline is to cut all of the interface generated into the batch of highway diesel fuel. Discussion at a recent industry conference highlighted the fact that this practice will no longer be possible when all highway diesel fuel is required to meet a 15 ppm sulfur cap because of the relatively high sulfur content of jet fuel and kerosene (as high as 3000 ppm). It was stated that as a result the mixture of highway diesel fuel meeting a 15 ppm sulfur cap and jet fuel or kerosene would need to be

returned from the terminal to the refinery for reprocessing, at high cost (i.e. would need to be treated as transmix).

While we agree that handling procedures for this mixture will need to change, we believe that it will not be necessary to treat it as transmix. We believe that there will be opportunity for the mixture to be sold from the terminal into the off highway diesel pool or 500 ppm highway diesel pool during the period when the temporary compliance option is available. We have concluded that the increased volume of downgrade can be accommodated without disruption to the fuel market. The increased cost associated with downgrading this mixture is included in our analysis of distribution costs. The need for this additional downgrade results in an effective reduction in the supply of highway diesel fuel. The increased cost of supplying an additional volume of highway diesel fuel to compensate for this reduction is incorporated in our analysis of refinery costs. Additional storage tanks will be needed to handle the mixture at those terminals that currently do not handle off highway diesel fuel. The cost of these tanks has been fully accounted for in the calculation of costs during the time period when the optional compliance program is available.

iv. Conclusion

We conclude that the primary change needed to current distribution practices to limit sulfur contamination of 15 ppm highway diesel fuel in the pipeline system (and for the distribution system as a whole) will be the elimination of discretionary mixing of a fraction of the interface volume associated with pipeline shipments of highway diesel fuel into the highway diesel fuel pool. When the temporary compliance option expires, the additional volume of highway diesel fuel that will need to be downgraded to a lower value product as a result of this change will be sold into the off highway diesel fuel market. During the period when the temporary compliance option is available, we estimated that a fraction of this volume would be sold into the 500 ppm highway diesel fuel market. The relative volumes of downgrade that we expect will be sold into the off highway vs the 500 ppm highway diesel market and the costs associated this downgrade are discussed in section V.C. We concluded that the additional downgrade can be accepted without significant disruption to either the off highway or highway diesel fuel markets (see section IV.D.2.).

The need to produce an additional volume of 15 ppm highway diesel fuel to compensate for the additional downgrade is accounted for in both our feasibility and cost analysis (see Section IV.D.2. and V.C.). Given that in all cases there will be opportunity to downgrade the volume of interface which currently is blended into highway diesel fuel to a lower value product, we believe that the changes outlined above can be implemented without the generation of any significant additional volumes of transmix from this source. The Association of Oil Pipelines stated that pipeline operators may more frequently abut batches of highway diesel fuel with batches of low sulfur gasoline in an attempt to limit sulfur contamination of highway diesel fuel meeting a 15 ppm cap.⁶⁰ If this were the case, additional volumes of transmix would be

generated since mixtures of gasoline and diesel fuel must typically be returned to the refinery for reprocessing. The changes to pipeline interface practices described in this section will be sufficient to limit sulfur contamination from high sulfur products that abut batches of 15 ppm highway diesel fuel in the pipeline. Pipeline operators will not be forced to increase the frequency that batches of gasoline abut batches of highway diesel fuel in the pipeline. Since we expect that no changes will be needed in the choice of products that abut highway diesel fuel in the pipeline, we believe that no significant additional volume of transmix associated with pipeline interface will be generated as a result of our program.

During the time period when the temporary compliance option is available, the ability to abut some batches of 15 ppm highway diesel fuel with batches of 500 ppm highway diesel fuel in pipelines that carry both fuels may ease the difficulty limiting sulfur contamination of 15 ppm fuel. We believe that it will still be necessary to cut all of the interface between such products into the 500 ppm fuel batch. Nevertheless, the lower sulfur content of 500 ppm highway diesel fuel relative to off highway diesel fuel would mean that whatever mixing that does take place from would have less impact on the sulfur content of 15 ppm highway diesel fuel.

b. Identifying the Location of the Interface Between Fuel Batches

The Association of Oil Pipelines (AOPL) expressed concern that their current physical methods of evaluating when to make a cut between adjacent batches in the pipeline may not be adequate for determining when a cut should be made between a batch of 15 ppm diesel fuel and a batch of a different product adjacent to it in the pipeline.⁶¹ AOPL related that pipeline operators currently do not use the measurement of fuel sulfur content to help determine when such a cut should be made. They related that there would be no time to conduct a lab evaluation of fuel sulfur content and that appropriate on-line sulfur measurement equipment is currently not available. The recent National Petroleum Council (NPC) clean fuels report stated that they did not expect that field test equipment such as that which might be used to measure the sulfur content of fuel as it flows through the pipeline would be available by the time our sulfur control program is implemented.⁶²

We do not believe that pipeline operators will need to substantially change the methods used to detect the interface between highway diesel fuel and adjacent products in the pipeline. We believe that the difference between the physical properties of highway diesel fuel and other products carried in the pipeline will continue to be as identifiable as they currently are. Therefore, pipeline operators will have the same ability to discern the interface between two products in the distribution system based on a change in fuel density and/or a change in color. In addition, pipeline operators are already coping with instances where the physical properties of fuels in the pipeline is very similar. When the normal methods of detecting an interface between batches are thought to provide insufficient differentiation between batches, pipeline operators in some cases today inject a small amount of dye or other fuel marker at the start of a new batch to distinguish it from a previous batch. We expect this practice will continue in the future.

Tracking information from upstream in the pipeline is also used to help identify the approximate time when the interface between batches will arrive at a given point in the system. This helps to focus the attention of technicians who make the cuts between pipeline batches during the time when the interface is expected to pass their observation post.

Making a protective interface cut will likely be critical to adequately limit sulfur contamination during the distribution of 15 ppm diesel fuel. This may force additional measures to ensure that there will be adequate time for the cut to be made. Such measures may include: more rapid communication between the station at which the fuel is sampled in the line and the control room where the valves are operated, providing means to control the valves at the point where the product in the pipeline is measured, or moving the sampling point further upstream in the pipeline. We believe that the need for such changes will be made within the context of optimizing the distribution system to limit contamination. The costs of these changes are accounted for in our cost estimate for this optimization process and should not cause a significant disruption to pipeline operations.

c. Dead Legs

Dead legs are lengths of pipeline extending off from a main line (e.g. to serve a terminal tank farm) that have a valve situated some distance from the junction of the two lines. There is potential for some mixing of the fuel left in the dead leg (e.g. after an exchange of products between a terminal and the pipeline) with other batches of fuel as it passes in the main pipeline. If such mixing occurs quickly, the product left in the dead leg would tend to be included in the interface between adjacent products in the pipeline. For short dead legs, we believe that the turbulence at the junction of the two lines will ensure that this is the case. If a dead leg was long enough, some product might remain trapped near the valve in the dead leg. During the operation of a pipeline it is common for pressure fluctuations to occur. Such fluctuations could cause product trapped in a long dead leg to be drawn out into the pipeline stream over time, resulting in some contamination of a batch as it passes the dead leg. Commenters stated that the sulfur contamination of highway diesel fuel from dead legs could be significant when the 15 ppm cap on sulfur content is implemented.

We believe that existing concerns about limiting contamination has ensured that existence of long dead legs is the exception rather than the rule. Such concerns will have already provided a strong incentive to keep the volume of fuel contained in a dead leg to an minimum by careful placement of the valve close to the junction of the lines. To the extent that there may still be some long dead legs in the system, compliance with the Tier 2 gasoline sulfur requirements will encourage their elimination well before the implementation of our diesel sulfur program. To the extent that long dead legs exists when our diesel sulfur program is implemented, the problem can be rectified by properly repositioning the valve. Given the limited extent that such instances are likely to exist, this should not be a significant burden to the pipeline industry. The potential cost of such valves is small enough to be accommodated in the costs we have attributed to the

optimization of the distribution system to limit sulfur contamination (see section V.C.3.). We believe that any instances where long dead legs do exist, will be identified and rectified before the 15 ppm sulfur standard for highway diesel fuel is implemented. Given that most, if not all dead legs, are already relatively short, and the fuel in such dead legs is exchanged in the interface between fuel batches as they pass the leg in the pipeline, the highway diesel fuel downgrade volume from such sources is already factored into our analysis of downgrade volumes (see section IV.D.2.a.).

d. Line-Fill

Prior to the injection of fuel into a pipeline, the feed line from the terminal or refinery tanks holding the batch of fuel to be injected must be “laid down” (filled) with the product to be injected. There is a like situation at the tank farms where product is transferred from a main pipeline to a branch line or to another operators pipeline. The term line-fill refers to the amount of fuel in the feed line(s) from a tank farm to a pipeline. When product is received at a terminal from the pipeline, the product which is resident in the feed line must be purged. To facilitate the exchange of products in the feed line, most facilities have at least two lines from the pipeline to the tank farm. When possible, the fuel that must be displaced from the feed line is directed to a tank that contains the same product. However, inevitably some fuel will need to be directed into a “slop tank” to be treated as transmix. Pipeline operators keep records of the products resident in the various line segments to ensure proper routing and separation of product when the line is being laid down.

Line-fill volume is fixed and will not increase as a result of our program. Pipeline and terminal operators will need to exercise additional care to limit the mixing of high sulfur products into highway diesel fuel when preparing for the injection of a batch of highway diesel fuel into the pipeline. However, given the relatively small diameter and length of lines used in this process, there should be little or no increase in the amount of interface or transmix generated. Thus, there should be no need for additional tanks to handle transmix and little or no impact on the difficulty and costs associated with the line-fill process.

An analogous situation occurs when product is drawn off of the pipeline into a stationary storage facility (terminal or pipeline brake out facility). The product contained in the receiving line (which can also be used to inject products into the pipeline) must be properly directed when receiving a batch of highway diesel fuel. For the reasons discussed above, the implementation of our sulfur program should also not result in the a significant impact related to drawing fuel off of the pipeline.

e. Leaking Valves

Contamination from leaking valves is a greater concern from single-seal valves. Existing concerns about product contamination has encouraged the increased use of double-seal valves

throughout the distribution industry. As a result, much of the system already uses such valves and there is an increasing trend towards their use. In addition, it is common practice to monitor valves to ensure their proper operation. Therefore, there should be little potential for sulfur contamination of 15 ppm highway diesel fuel from leaking valves. We anticipate that at those locations where double-seal valves are not already utilized, distributors may be encouraged to install such valves by the implementation of the Tier 2 gasoline sulfur requirements. To the extent that single-seal valves continue to be in use when our diesel sulfur program is implemented, our diesel program may further accelerate their replacement with double-seal valves.^x We expect that the locations where such replacement is advised will be identified during the process of optimizing the distribution system to limit sulfur contamination in 15 ppm highway diesel fuel, and that their installation where needed will not be burdensome.

f. Surface Accumulation of Sulfur-Containing Substances

The specter was raised in the comments on the NPRM that sulfur contamination from the accumulation of substances on the walls of the pipeline and on the surfaces of stationary storage tanks and the tank compartments in tank trucks, tank wagons, rail cars, and barges could jeopardize the ability to comply with the 15 ppm cap on highway diesel fuel. No other information was provided to substantiate this concern. We believe there is no reason to surmise that contamination from surface accumulation in pipelines will represent a significant concern under our sulfur program. To the extent that sulfur-containing molecules in a fuel batch adhere to the wall of a pipeline, they would tend to be flushed back into the pipeline flow in the interface between products. Whatever amount that might tend to tenaciously adhere to pipeline walls would tend to remain in an aggregate formation rather than dissolving back into the stream. Such accumulation would either be removed as part of normal pipeline cleaning processes, or if flaked off into the pipeline flow, would be removed during the normal filtration process. To the extent that products accumulated on pipeline walls might dissolve back into the pipeline flow, this would be more likely to occur into lighter products which act as solvents such as gasoline. Based on the above discussion, we believe that contamination from surface accumulation in pipelines will not represent a significant concern. For these same reasons, we expect that surface accumulation in storage tanks will not pose a significant contamination concern. In addition, to the extent that contamination from surface accumulation may be a concern, it seems reasonable to conclude that this issue would already be an issue since highway diesel fuel is very sensitive to dye contamination from off highway diesel fuel.

To adequately limit sulfur contamination, it may become more important to allow sufficient time for high sulfur fuel clinging to the walls of tanks to drain completely before

^x Double valves were used to help prevent lead contamination from leaded to unleaded gasoline during the phase-out of lead in U.S. gasoline. The lead phase-out presented perhaps the most difficult situation with respect to limiting contamination up to this time.

refilling the tank 15 ppm highway diesel fuel. However, this represents only more careful observation of what is current industry practice and should not impose a significant burden. Such concerns are discussed further in the section on limiting sulfur contamination at stationary storage facilities and during transportation by surface vehicles and marine vessels.

3. Limiting Sulfur Contamination at Stationary Storage Facilities

This section addresses the following concerns related to limiting sulfur contamination at stationary storage facilities such as terminals, bulk plants, and pipeline break-out tank farms:

- Quality control testing
- Switching products contained in storage tanks:
Contamination from high sulfur product left behind in a storage tank that will be used to contain highway diesel
- Tank manifolds:
Contamination from high sulfur product contained in lines that connect various storage tanks to a common fuel transfer point such as a terminal rack

Because of their crosscutting nature, the following concerns regarding the limitation of sulfur contamination at stationary storage facilities were addressed in the previous section on limiting contamination in the pipeline system:

- The need for additional storage tanks at certain terminals to accommodate a needed change in the interface handling practices with respect to batches of highway diesel fuel that abut batches of jet fuel or kerosene in the pipeline
- Line fill
- Leaking valves
- Surface accumulation of high sulfur product

a. Quality Control Testing

We believe that a modest level of additional quality control testing will be needed at the terminal level to ensure compliance with the 15 ppm sulfur cap. Further, we believe that such additional testing can be conducted using existing equipment and will not represent a substantial burden to industry. For additional discussion regarding the extent and costs of this testing please see section V.C.3 in this RIA. For a discussion of the test procedures we expect will be used to

measure the sulfur content of highway diesel fuel please see section VII in the preamble the final rule for our diesel sulfur program.

b. Product Switching in Stationary Storage Tanks

In some instances, different products are held in the same tanks at different times. This can occur at the tank facilities which are a part of the pipeline system, such as the facilities which feed product into pipelines and at break-out tank facilities.^y During the switching of products held in a storage tank, sulfur contamination may result from high-sulfur product left behind in the tank before being filled with highway diesel fuel. The foremost potential source of residual product left behind during such switching operations is the tank heel. A tank heel is the amount of product that remains in a tank after no additional product can be removed by normal means. Pipeline operators have expressed concern that a tank heel volume of off highway diesel fuel that today can be mixed with an incoming batch of highway diesel fuel without causing the current 500 ppm cap to be exceeded, would cause the 15 ppm cap to be exceeded.⁶³ In such cases the tank would need to be flushed before 15 ppm diesel fuel could be placed in it. This concern was expanded upon by the Independent Fuel Terminal Operators Association (IFTOA) who stated that storage tanks would need to be chemically cleaned before being used to store 15 ppm diesel and be dedicated to holding only 15 ppm highway diesel fuel thereafter.⁶⁴

The amount of tank heel varies depending on the type of tank floor. Some tanks have a conical shaped floor typically constructed of concrete with a drain at the lowest point. The tank heel for such a tank is nearly zero. New tanks are typically constructed with such a floor so that they will drain completely. This greatly facilitates tank maintenance and facilitates the easy removal of water that settles at the bottom of the tank.

Some (primarily older) tanks have a roughly level sand floor on which a liner rests. Such tanks may or may not have a number of drains at various low points in the tank to facilitate the elimination of water that settles to the bottom. The floors of such tanks can be quite irregular and contain a number of low areas where fuel pools and can not readily be removed. This volume is the tank heel. In addition, such tanks may have a side drain rather than a floor drain, which can contribute further to the volume of the tank heel. The volume of the tank heel for such tanks can be substantial. Therefore, high sulfur product in the tank heel could be a significant source of sulfur contamination.

One fact which tends to limit the potential sulfur contamination from residual high sulfur products in the flat bottom tanks is that water tends to settle into stagnant areas at the bottom of a tank. This limits the volume of petroleum products that can reside in such stagnant areas since

^y An example of a break-out tank facility is one that holds products the are stripped off of a main pipeline before injection into another line.

they tend to be filled with water. The water trapped in stagnant pools on the bottom of a tank is a concern in and of itself. Biological organisms can grow at the interface between water and petroleum products, especially diesel fuel. The residue from such organisms can cause significant contamination. These concerns have contributed to the trend away from the use of tanks with an irregular flat bottom. More importantly, the majority of storage tanks used to hold highway diesel fuel are currently dedicated to this purpose and there is an increasing trend towards this practice. It seems reasonable that due to the difficulty in switching the products contained in storage tanks with irregular flat bottoms, such tanks would be the first tanks to be dedicated to a single fuel. In the infrequent cases where this is not already the case, it seems reasonable that where practicable the tank would be dedicated to a single fuel. In such cases, only a one time cleaning would be required.

To the extent that some additional dedicated tankage will be necessary, we have more than compensated for this in our analysis of the additional tanks that will be needed to facilitate the presence of two grades of highway diesel fuels during the period covered by the temporary compliance option. We have assumed that such tanks will be constructed at a number of stationary storage facilities and anticipate that most storage facilities will have a dedicated tank to handle 15 ppm diesel fuel. We also estimated that additional storage tanks may be needed at some tank farms that service the pipeline system due to a change in the interface handling practices regarding batches of highway diesel fuel and jet fuel or kerosene that abut each other in the pipeline (see section IV.D.2.a. in this RIA). This also helps to compensate for whatever additional tanks might be needed to address contamination concerns. The costs for these tanks is incorporated in our estimation of tank costs to facilitate handling two grades of highway diesel fuel during the period when

It seems likely that storage tanks would need to be flushed with highway diesel fuel prior to being switched from containing off highway diesel fuel, jet fuel, or kerosene to 15 ppm highway diesel fuel. We do not believe that there is any reason to suspect that the tank would need to be chemically cleaned to remove residual high-sulfur products clinging to the interior surfaces of the tank.^z It should be noted that due to concerns about dye contamination from off highway diesel fuel and the impact of gasoline on the flash point of highway diesel fuel, properly emptying a tank to hold highway diesel fuel is already a significant concern. Consequently, it is not uncommon currently for a storage tank to be flushed with a quantity of highway diesel fuel prior to being filled with highway diesel fuel if the previously held gasoline or off highway diesel fuel. We believe that following such normal business practices when switching products contained in a storage tank in most cases would provide sufficient protection against sulfur contamination in 15 ppm highway diesel fuel. Some additional volume of highway diesel fuel may need to be used in flushing tanks before switching a storage tank to highway diesel fuel

^z See the earlier discussion on potential contamination from high sulfur products clinging to the walls of pipelines (IV.D.1.e.).

service when our 15 ppm sulfur cap is implemented. However, because such switching occurs infrequently, we believe that additional amount of downgrade caused by tank flushing will be insignificant. In addition, our use of conservative assumptions in estimating the additional downgrade volume from the changes needed in interface handling practices will more than offset any additional downgrade volume that may result from tank flushing.

c. Tank Manifolds

The array of tanks at tank farms is connected by a network of pipes that resemble the network of rail lines at a railroad yard. At the juncture between the feed lines from the pipeline and the tank manifold system, a branching takes place such that products directed toward two different tanks may flow down a single connecting line for a time. Similar to the line fill situation, product downgrade and transmix can result from different products sharing the same line. To the extent that the tank that contains highway diesel fuel is located at the end of the pipe network, there may be more opportunity for mixing of high sulfur products into a batch of highway diesel fuel as it moves through the manifold to and from the storage tank.

When off highway diesel fuel abuts highway diesel fuel in a tank manifold, it is common practice to make a protective interface cut between the two batches (i.e.: all of the mixed product is cut into the off highway diesel fuel). This practice is followed because the interface volumes in manifold pipes are small and there is little incentive or ability to fine tune the amount of interface which is cut into the different fuel batches. We expect that this procedure will continue in the future and will be sufficient to limit the sulfur contamination of 15 ppm highway diesel fuel in tank manifold systems. Therefore, we believe that the handling of 15 ppm highway diesel fuel in tank manifold systems will not result in the generation of significant volumes of additional product that must be downgraded to a lower value product or treated as transmix. Another factor which tends to minimize concerns related to tank manifolds is that only a small volume of product resident in the pipe networks must be displaced when moving a batch of highway diesel fuel, even in those cases where the storage tank that holds the highway diesel fuel is at the end of the manifold system.

As discussed in the previous section, we estimated that many facilities will construct an additional tank dedicated to 15 ppm diesel fuel. To the extent that contamination concerns exist regarding the placement of highway diesel fuel storage tanks in the manifold system, we anticipate that new tanks will be located in a way that minimizes these concerns.

4. Limiting Sulfur Contamination During Transport by Surface Vehicles

Highway diesel fuel is transported by the following types of surface vehicles: tank truck, tank wagon, and rail car. Tank trucks are the largest capacity road haul vehicles that carry

petroleum products. They deliver product to truck stops, service stations, and large fleet operators, as well engaging in other road movement of petroleum products as needed. Tank wagons usually serve smaller customers, such as centrally-fueled fleets, smaller service stations, and in certain circumstances heating oil customers such as homeowners. Tank wagons normally have multiple tank compartments to accommodate the delivery of several different fuel types in a single delivery circuit. Tank wagons have a smaller total capacity than tank trucks. In cases where pipeline service is limited, fuel is sometimes shipped to the terminal by rail car.

In the proposed rule, we stated that concerns related to limiting sulfur contamination during the transport of 15 ppm diesel fuel by tank truck, tank wagon, and rail car could be adequately addressed by careful and consistent observation of current industry practices used to limit contamination. Based on this assessment, we concluded that our program would result in a significant additional burden regarding the transportation of highway diesel fuel by such vehicles.

The Independent Fuel Terminal Operators Association (IFTOA) stated that all storage tanks, including those on surface transport vehicles would need to be chemically cleaned before being used to store 15 ppm diesel and would need to be dedicated to this purpose thereafter.⁶⁵ The American Petroleum Institute (API) stated that it is unlikely that “consistent and careful” observation of current practices will be sufficient to limit sulfur contamination during transport of 15 ppm diesel fuel as EPA asserted in the proposed rule.⁶⁶ The American Trucking Association (ATA) stated that our assertion that enhanced observation of current industry practices by truckers that distribute highway diesel fuel was incorrect.⁶⁷ ATA argued that an additional burden results whenever a trucker must alter current handling practices and that this additional burden would impact truckers who are small businesses the most. ATA offered no additional detail on the nature of the potential burdens. We did not receive information to substantiate the concerns raised in these comments.

In their comments on the Advance Notice of Proposed Rulemaking (ANPRM), the Petroleum Marketers Association of America (PMAA) stated that contamination concerns would cause a large number of tank wagon operators to purchase new trucks with dedicated tank compartments for 15 ppm highway diesel fuel and dedicated delivery systems.⁶⁸ PMAA stated that this would cause much disruption to the fuel distribution industry and an unacceptable burden to its members. We responded to these comments from PMAA in the Draft Regulatory Impact Analysis (DRIA) for the proposed rule.⁶⁹

We continue to believe that sulfur contamination during the transport of 15 ppm diesel fuel by tank truck, tank wagon, and rail car can be adequately controlled by the careful and consistent observation of current industry practices used to limit contamination. These practices include making sure that the tank truck, tank wagon, or rail car is properly leveled and allowing sufficient time for the tank compartment to drain completely prior to filling with 15 ppm highway diesel fuel. The tank compartments in such vehicles are designed to drain completely. As discussed earlier (see section IV.D.2.e.), we do not believe that the accumulation of high

sulfur products on the walls of storage tanks will be significant source of sulfur contamination. Therefore, assuring that such compartments drain completely will be sufficient to limit sulfur contamination. There are no unique concerns related to limiting contamination during the transport of 15 ppm highway diesel fuel by tank trucks and rail car.

PMAA stated that it would not be possible to adequately limit sulfur contamination when delivering 15 ppm highway by a tank wagon that has a common delivery system. In such cases, the delivery system would need to be purged of high-sulfur product prior to its use to delivery 15 ppm highway diesel fuel. Current industry practice is to switch the product flow just prior to the end of the delivery so that the delivery system is charged with the product intended for delivery at the next stop. PMAA stated that this is not always feasible because the receiving tank may fill more quickly than was expected, or the next customer may not need the product that has been put into the hose. We believe such occurrences will be rare and can be further limited by more careful filling and delivery scheduling practices. Tank wagon operators currently schedule deliveries of highway diesel fuel as a first stop in the delivery circuit whenever possible to help minimize contamination concerns.

In transitioning from the delivery of off highway diesel fuel to highway diesel fuel, PMAA related that after switching to highway diesel fuel at the end of the delivery of off highway diesel, tank wagon operators typically observe the color of the product being delivered and do not turn off the flow until the stream is clear. Since off highway diesel (including heating oil) typically contains a red dye, a clear stream indicates that the delivery system is completely flushed of off highway diesel fuel. This practice will continue to be sufficient to ensure that the delivery system is charged with highway diesel fuel since a minute quantity of dye causes a visible trace in highway diesel fuel (see section IV.D.1).

Since the practices described above are currently in common use due to existing product contamination concerns, we continue to believe that there should be not be a significant additional burden associated with ensuring their consistent and careful observance. Some marketers may need to reeducate their employees regarding the importance of these practices. To the extent that such employee education is needed at all, we anticipate that it might be accomplished in regular employee meetings or employee bulletins at negligible cost.

In any event, the concerns discussed above should represent the exception rather than rule. Most highway diesel fuel is distributed to retail facilities and centrally fueled fleets where off highway diesel fuel is not used. Thus, the circumstances where the same tank compartment is used to alternately handle off highway and highway diesel fuels are limited. This also means that cases where a tank wagon's delivery circuit includes off highway diesel fuel would be limited. Such cases would primarily be limited to areas where diesel fuel oil is used for home heating, such as in the North-East during the home heating season.

More importantly, the tank compartments in tank trucks and tank wagons are for the most part dedicated to carry a single fuel. In addition, most tank wagons have a separate delivery system for each product. Further, there is an increasing industry trend towards dedicating such equipment to handle a single fuel. In cases where such dedication exists, sulfur contamination will not be a concern. Thus, the circumstances under which the concerns discussed above arise are expected to be uncommon and to decrease over time.

5. Limiting Sulfur Contamination During Transport by Marine Vessels

The Independent Fuel Terminal Operators Association (IFTOA) stated that the current practice of flushing tanks on a barge with fuel when a supplier switches from a fuel with a higher sulfur content to highway diesel fuel would no longer be possible when the 15 ppm cap on the sulfur content of highway diesel fuel is implemented.⁷⁰ IFTOA stated that it would be necessary to clean the tank compartments with high powered water jets which is a difficult and expensive process (\$30,000 to \$50,000 per barge).

During the three month transition period between the time when refiners are required to produce 15 ppm highway diesel fuel and when it is required downstream, we anticipate that distributors stationary storage tanks will gradually be blended down so that any residual product is removed. Thus, for dedicated stationary storage tanks we expect that contamination from residual high sulfur fuel will not be a significant concern. Similar to stationary storage tanks, we expect that barges will experience sufficient turn overs of the fuel contained in their tank compartments to ensure that sulfur contamination from residual high sulfur product is not a significant concern.

It may be reasonable to presume that barges are equipped with sumps from which the residual product can be completely removed. If this were the case, one might conclude a barge could be made ready to carry 15 ppm highway diesel fuel by allowing sufficient time for fuel to drain into these sumps to be removed. If this were not sufficient, flushing the barge with 15 ppm diesel fuel might provide the necessary cleaning action. If this were so, the situation would be similar to that discussed above for stationary storage tanks, for which we concluded that sulfur contamination from residual product should not be a significant concern.

Due to existing contamination concerns, most tank compartments in marine vessels used to transport highway diesel fuel are already dedicated to this purpose and there is an increasing trend toward such dedication. Some barges plying the eastern seaboard may on occasion switch seasonally between highway diesel and heating oil. However, this is the exception rather than the rule. Consequently, we expect that there would be few instances when this concern would arise which would decrease in time. To the extent that such instances might occur, we believe that the associated tank cleaning costs would not substantially add to the cost of our program. In

addition, the volume of heating oil shipped under such circumstances is small fraction of the total volume shipped by barge. Hence, any impact would be insignificant in the context of our entire program.

We received no comments to suggest that there are unique concerns for other marine vessels such as coastal tankers.

6. Limiting Sulfur Contamination from Diesel Fuel Additives

Diesel fuel additives include corrosion inhibitors, cold-operability improvers, and static dissipaters. Use of such additives is distinguished from the use of kerosene by the low concentrations at which they are used and their relatively more complex chemistry.^{aa} We proposed that diesel fuel additives used in highway diesel fuel meet the same cap on sulfur content required for the fuel itself. Additive manufacturers commented that there was no need to impose a 15 ppm sulfur cap on such additives in order to effectively limit the sulfur content of finished diesel fuel.⁷¹ They asserted that imposing such a cap would result in unjustified costs and disruptions to the producers and users of diesel additives. Additive manufacturers also stated that for certain additives, such as static dissipaters needed to prevent explosion hazards at terminal facilities, there are currently no effective alternatives that comply with a 15 ppm cap on sulfur content.

In response to these comments, we are allowing the use of diesel fuel additives with a sulfur content greater than 15 ppm provided their use does not result in an exceedence of the 15 ppm cap on the sulfur content of highway diesel fuel.

Our review of data submitted by additive and fuel manufacturers to comply with EPA's Fuel and Fuel Additive Registration (F&FAR) requirements (40 CFR Part 79), which is summarized below, indicates that additives to meet every purpose (including static dissipation) are currently in common use which meet a 15 ppm cap on sulfur content. The ability of industry to provide additives for use in 15 ppm highway diesel fuel is further supported by the fact that diesel fuel meeting a 10 ppm cap on sulfur content has been marketed in Sweden for some time, and ARCO Petroleum recently began marketing fuel meeting a 15 ppm sulfur cap in California. Even if low sulfur additives were not yet available for certain purposes, we believe that it is reasonable to assume that they would become available before our sulfur program is implemented in 2006. The summary of the data in the F&FAR database also indicates that the

^{aa} Diesel fuel additives are used at concentrations commonly expressed in parts per million. Diesel fuel additives can include specially-formulated polymers and other complex chemical components. Kerosene is used at much higher concentrations, expressed in volume percent. Unlike diesel fuel additives, kerosene is a narrow distillation fraction of the range of hydrocarbons normally contained in diesel fuel. See Section VII.C.4. above regarding the requirements associated with the addition of kerosene to diesel fuel.

industry could adapt to use only additives that contain less than 15 ppm sulfur. However, we agree that it is not necessary to force the additives that contain greater than 15 ppm sulfur to be retired. By allowing their continued use, we avoid any significant impacts from our sulfur program related to diesel fuel additives.

Summary of Information Contained in the F&FAR Database on Diesel Fuel Additives

- Most sulfur containing additives registered with the EPA currently meet the 15 ppm cap.
 - There are approximately 3500 diesel additives registered with the EPA.
 - Of the diesel additives registered with EPA, 463 additives manufactured by 104 companies contain sulfur.
 - Of the sulfur-containing additives, 176 additives (38 of such additives) manufactured by 51 companies (49 of companies that manufacture sulfur-containing additives) have a sulfur content greater than 15 ppm
 - There are 226 sulfur-containing additives manufactured by 65 companies that have a sulfur content less than 5 ppm.
- In 1999, 5.5 percent of the total volume the additives used in diesel fuel contained sulfur.
- In 1999, 47 percent of the diesel fuels registered by fuel manufacturers had sulfur containing additives listed (of all purposes in-use). These fuel formulations represent 65 percent of the total diesel fuel volume.
- Several dozen different additives registered with EPA have anti-static (static dissipater) listed as a purpose in-use (PIU). EPA data shows that there are 40 additives that list anti-static as a PIU.
 - 64 percent of these additives have an elemental sulfur level greater than 15 ppm.
 - Nearly a dozen different anti-static additives registered with the EPA have zero amount of sulfur in their formulations.

Since such off highway additives are currently in widespread use side-by-side with high-sulfur additives, it is reasonable to conclude that there is not a significant difference in their cost.

The unusually high sulfur content of a few additives may discourage their use in diesel fuel that meets a 15 ppm sulfur cap. However, it will generally continue to be possible for additive manufacturers to market additives that contain greater than 15 ppm sulfur for use in highway diesel fuel. Such additives can also continue to be used in off highway diesel fuel. Additive manufacturers that market such additives and blenders that use them in highway diesel fuel will have additional requirements to ensure that the 15 ppm sulfur cap on highway diesel fuel is not exceeded. Although our sulfur program may encourage the gradual retirement of additives that do not meet a 15 ppm sulfur cap for use in highway diesel fuel, we do not anticipate that this will result in disruption to additive users and producers or a significant

increase in cost. Additive manufacturers commonly reformulate their additives on a periodic basis as a result of competitive pressures. We anticipate that any reformulation that might need to occur to meet a 15 ppm sulfur cap will be substantially accommodated within this normal cycle.

In some cases, blenders may not find it feasible to conduct testing, or otherwise obtain information on the sulfur content of the fuel either before or after additive blending, without incurring substantial cost. Without such information, a blender would not have documentation with which to evaluate what impact the use of an additive which exceeds 15 ppm would have on the fuel's final sulfur content.^{bb} We anticipate that blenders will manage the risk associated with the use of additives above 15 ppm in sulfur content under such circumstances with actions such as the following:

- selecting an additive with minimal sulfur content above 15 ppm that is used at a low concentration, and
- working with their upstream suppliers to provide fuel of sufficiently low sulfur content to accommodate the small increase in sulfur content which results from the use of the additive.

This is similar to the way distributors will manage contamination from their distribution hardware (tank trucks, etc.). Distributors will not necessarily test for fuel sulfur content after each opportunity for contamination, but rather will rely on mechanisms set up to minimize the contamination, and to obtain fuel sufficiently below the standard to accommodate the increase in sulfur content from the contamination.

7. Handling Batches of Highway Diesel Found to Exceed the Sulfur Standard Downstream of the Refinery

We believe that there will not be a significant increase in the volume of highway diesel fuel discovered to exceed the sulfur standard downstream of the refinery as a result of today's rule. We believe this will be the case both during the transition of the program and after the sulfur requirements are fully implemented. We anticipate that distributors will quickly optimize their practices to avoid sulfur contamination. We also anticipate that distributors will gain some

^{bb} The transfer of an additive with a sulfur content greater than 15 ppm will be required to be accompanied by a product transfer document which provides information in the sulfur content of the additive and the extent to which its use at the maximum recommended concentration would increase the sulfur content of the finished fuel. This information will allow the blender to assess the potential impact of the additive's use on their compliance with the requirement that the use of additives not cause the 15 ppm cap on the sulfur content of highway diesel fuel to be exceeded.

experience in reducing sulfur contamination in the distribution system through complying with the recently finalized Tier 2 low sulfur gasoline requirements (65 FR 6698, February 10, 2000). While outside the scope of this final rule, it is worth pointing out that potential difficulties in distributing 15 ppm diesel fuel would be lessened if the sulfur content of off highway diesel fuel is reduced by a future rulemaking. We anticipate that the batches of highway diesel fuel that are discovered to exceed the 15 ppm sulfur cap will be coped with as follows:

- When possible, by blending highway diesel fuel that is below the 15 ppm cap with the out of specification batch to bring the resulting mixture into compliance. This practice will be more difficult than it is currently because the amount of fuel needed to blend the out of specification batch into compliance may increase. However, we expect it to continue to be the method of choice for handling out of specification highway diesel whenever possible.
- By downgrading the batch either to off highway diesel fuel or to 500 ppm highway diesel during the initial years of our program when the temporary compliance option is available.
- By reprocessing the batch to meet the 15 ppm cap, but only in those infrequent instances where the previous options do not exist.

We do not believe that the cost of handling out-of specification highway diesel batches will increase significantly as a result of our sulfur program.

E. Misfueling

1. Introduction

As noted in the feasibility discussion of Chapter III, we believe that, in order to comply with the 2007 and later model year heavy-duty diesel engine emission standards, low sulfur diesel fuel is needed. For this reason, refiners will be required to begin producing 15 ppm sulfur highway diesel fuel starting in mid-2006. Once 2007 and later model year heavy-duty vehicles are sold and operated in the fleet, it will be very important that these vehicles are refueled with low sulfur fuel to ensure proper operation of the emission control systems. Misfueling a 2007 and later model year heavy-duty vehicle with a fuel that has a sulfur level above 15 ppm could poison the emission control system and eliminate any emissions benefit from the 2007 standards.

There is the potential for misfueling a 2007 and later heavy-duty vehicle because there are a number of situations where vehicle owners could have access to diesel fuels with sulfur levels significantly above 15 ppm. First, hardship provisions allow small refiners to continue producing and selling as highway fuel, current highway diesel fuel (which can have a sulfur level of up to

500 ppm) until mid-2010. Second, we are adopting a temporary compliance option that allows refiners to continue producing current highway diesel during the transition of the program. Third, even without the temporary compliance option for highway diesel fuel, off highway diesel fuel (which can have a sulfur level of up to 5,000 ppm) will continue to be available in the market. Last, United States vehicles operated in Canada or Mexico may have access to fuels that do not meet the 15 ppm sulfur limit being adopted for the United States.

Misfueling can happen for a number of reasons. A vehicle owner may choose to misfuel deliberately if they perceive there would be an economic benefit to doing so. For example, misfueling was a significant problem during the transition from leaded gasoline to unleaded gasoline in the mid-1970s and 1980s when unleaded gasoline was required to be used in 1975 and later model year cars. On average, leaded gasoline was significantly cheaper than unleaded gasoline at the retail level and provided a strong incentive for some owners to misfuel with the wrong fuel. A vehicle owner may also misfuel accidentally, and not even realize they are using the wrong fuel. This situation could happen currently at those retail outlets which carry both highway and off highway diesel fuel, and could happen during the transition period to low sulfur diesel fuel when both 15 ppm and 500 ppm sulfur will be available.

Depending on the level of concern over misfueling, there are a range of options that could be taken to limit the occurrence of misfueling. Options include simple, low cost programs that require labels on the fuel pump and labels on the vehicle that specify what fuel should be used in a vehicle, or color-coding nozzles to alert operators to what fuel is being pumped. More complicated and higher cost options include setting fuel nozzle size limits and fuel inlet restrictors, or requiring computer chips on fuel pumps and vehicles that allow the vehicle and fuel pump to “talk to each other” and ensure that the vehicle is getting the appropriate fuel.

The following section presents the steps being taken in this rule to ensure that 2007 and later model year heavy-duty diesel vehicles will be fueled with 15 ppm sulfur fuel. We then present our analysis of whether the steps being taken are sufficient to address concerns over misfueling. The misfueling discussion is divided into two sections addressing deliberate misfueling and accidental misfueling separately.

2. What Provision Are We Adopting to Ensure 2007 and Later Heavy-Duty Diesel Vehicles Use 15 ppm Sulfur Fuel?

As noted above, there are a number of situations where vehicle owners could have access to diesel fuels with sulfur levels significantly above 15 ppm. In order to ensure that operators of 2007 and later model year heavy-duty diesel vehicles are able to identify the proper fuel needed in their vehicle when they refuel, we are adopting the following provisions. First, model year 2007 and later heavy-duty diesel vehicles must be equipped with labels on the dashboard and near the refueling inlet that say: “Use Low Sulfur Diesel Fuel Only.” Second, heavy-duty vehicle

manufacturers must notify each purchaser of a model year 2007 or later diesel-fueled vehicle that the vehicle must be fueled only with low sulfur diesel fuel. We believe this requirement is necessary to alert vehicle owners to avoid high sulfur fuel that will be available in this country and outside the United States as well. Third, all highway diesel fuel pumps and co-located nonroad diesel fuel pumps must be prominently labeled to identify what type of fuel is dispensed from the pump.

3. Are Additional Requirements Necessary to Address Deliberate Misfueling?

A vehicle operator who deliberately misfuels will do so because they expect to realize some type of benefit from using the wrong fuel in the vehicle. The benefit the operator expects to realize might be economic (if the required fuel is more expensive than other fuels available) or it might be a performance benefit (if the operator believes the required fuel is inferior in some property to the other fuels available). For many heavy-duty diesel vehicles, particularly line-haul trucks, fuel costs can be as much as 20 percent of annual operating costs, so operators have a strong incentive to save on fuel costs. Therefore, one factor that would strongly encourage deliberate misfueling would be if there was a price differential between the 15 ppm sulfur diesel fuel (required for 2007 and later model year heavy-duty vehicles) and 500 ppm sulfur highway diesel fuel.

As described in Chapter V, the cost of producing 15 ppm sulfur fuel will be more expensive than current highway diesel fuel by approximately 4 cents per gallon. However, given the requirements adopted today, we believe there should not be a large price differential between the 15 ppm sulfur fuel and the 500 ppm sulfur fuel at retail outlets. Under the credit trading program, to produce 500 ppm fuel, most refiners will have to purchase credits from other refiners producing 15 ppm fuel, increasing the cost of the 500 ppm fuel, while decreasing the cost of the 15 ppm fuel. At the refinery gate, the cost of both fuels should be approximately the same. In addition, given the amount of 15 ppm fuel required under the temporary compliance option, 15 ppm fuel will be distributed through essentially the entire pipeline system. The distribution of 500 ppm fuel, on the other hand, will be more limited, due to its much lower volume. We expect that the 500 ppm fuel will be distributed by truck in the areas nearby refineries producing this fuel and through a few major pipelines to a limited number of major fuel consuming areas. Overall, the better economies of scale of transporting 15 ppm fuel should compensate for any additional handling cost due to the need to more carefully avoid contamination with high sulfur fuels. For these reasons, we expect the price to consumers of 500 ppm sulfur fuel to be generally close to that of 15 ppm sulfur fuel and, therefore, there should not be a significant economic incentive to misfuel with 500 ppm sulfur fuel. Nevertheless, any price differential could cause some operators to consider misfueling. Therefore, it is important to examine how price differential has affected misfueling in past fuel programs.

The main experience with any significant level of misfueling in the past was during the unleaded gasoline fuel phase-in that began in the mid-1970s. Throughout the early years of the unleaded gasoline phase-in, the retail price of unleaded fuel was typically around 7 to 8 cents per gallon more than leaded gasoline. This price differential represented ten percent or more of the average retail price of gasoline at the time.^{cc} Primarily because of this significant price difference, deliberate misfueling of cars with leaded fuel was a significant problem, resulting in poisoned catalytic converters and a loss of emission benefits. Based on the current retail price for highway diesel fuel from the Energy Information Agency of approximately \$1.60 per gallon, the small price difference expected under today's program between 15 ppm sulfur and 500 ppm sulfur fuels is expected to be significantly less (i.e., a price difference of around one to two percent) than the difference that existed between leaded and unleaded gasoline. With such a small difference in price between the 15 ppm and 500 ppm sulfur fuels, we do not believe there will be any significant short-term economic benefit for operators to misfuel 2007 and later heavy-duty vehicles.

Beyond the lack of an economic incentive, we believe there are several factors that will likely serve as deterrents to deliberate misfueling. First, the potential risk associated with voiding any manufacturer emission warranty or damaging the engine and exhaust system on an expensive vehicle might cause owners and operators of heavy-duty trucks to be more careful in ensuring that their vehicles are fueled properly. Second, as discussed in Section III.F. of this RIA, misfueled vehicles could experience a loss in performance, such as poor acceleration or engine stalling. Third, under our fuels regulations it is unlawful for any person to fuel a 2007 and later model year heavy-duty diesel vehicle with any fuel other than low sulfur highway diesel fuel.

With respect to the likelihood that operators would deliberately misfuel with nonroad diesel fuel, we do not believe the new fuel requirements will increase this likelihood. Nonroad diesel fuel is taxed significantly less than highway diesel fuel (approximately 24 cents per gallon less), so there is already a large price difference between the two fuels. Under the requirements of the new highway diesel fuel program, the price differential between highway and nonroad diesel fuels will stay the same or get slightly larger. However, any increase should be relatively minor and shouldn't result in any large increase in the likelihood of people deliberately misfueling with nonroad fuel.

The likelihood of deliberate misfueling in Canada is minimal and lessened by the prospects for eventual harmonization of standards. Canada has recently expressed its intent to

^{cc} DOE Comments on the NPRM, docket item IV-G-28, Enclosure 1.

harmonize its fuel regulations with our fuels standards.^{dd} This would offer vehicle owners the option of refueling with low sulfur fuel there. Even if Canada were to lag behind the U.S. in mandating low sulfur fuels, there is less potential for U.S. commercial vehicles needing low sulfur fuel to refuel in Canada because Canadian diesel fuel is currently much more costly than U.S. fuel due to higher fuel taxes. As a result, most vehicle owners will prefer to purchase fuel in the U.S., prior to entering Canada, whenever possible. This is facilitated by large tractor-trailer trucks that have long driving ranges of up to 2,000 miles per tankful and the fact that most of the Canadian population lives within 100 miles of the United States/Canada border. Consequently, most U.S. diesel vehicles would not have a critical need to refuel in Canada, and for those that do, low sulfur fuel would likely become available along major through routes to serve the needs of U.S. commercial traffic that have the need to purchase it.

With regard to Mexico, the entrance of U.S. trucks beyond the border commercial zone has been prohibited since before the conclusion of the North American Free Trade Agreement (NAFTA) in 1994. This prohibition applies in the U.S. as well, as entrance of Mexican trucks into the U.S. beyond the border commerce zone is also not allowed. Because these prohibitions are contrary to the intent of the Free Trade Agreement, a timetable was established to eliminate them.^{ee} However, these prohibitions remain in force at this time. As a result, there is little opportunity or need for misfueling in Mexico.

The NAFTA negotiations included creation of a "corridor" where commercial truck travel occurs, and where Mexico is obligated to provide "low sulfur" fuel. At the time of the NAFTA negotiations, "low sulfur" fuel was considered 500 ppm, which was the level needed to address the needs of engines meeting the 1994 emission standards. The travel prohibition currently in place may be lifted at some point. At that time, the issue of assuring, for U.S. vehicles, the availability of 15 ppm sulfur fuel needed by the 2007 and later heavy-duty vehicles may need to be addressed.

In summary, for the reasons described above, we do not believe there is cause for concern over any significant level of deliberate misfueling of 2007 and later heavy-duty vehicles. Although there is likely to be a limited amount of deliberate misfueling, we believe that people who are intent on deliberately misfueling will quickly find ways around any requirements

^{dd} "Process Begins to Develop Long Term Agenda to Reduce Air Pollution from Vehicles and Fuels", Environment Canada press release, May 26, 2000.

^{ee} See NAFTA, Volume II, Annex I, Reservations for Existing Measures and Liberalization Commitments, Pages I-M-69 and 70, and Pages I-U-19 and 20.

designed to limit misfueling. For example, based on our experience with unleaded gasoline^{ff}, many car owners physically removed the fuel inlet restrictor from their vehicles (which were meant to prevent an owner from refueling with the larger sized leaded fuel nozzles) so that they could refuel with cheaper leaded gasoline. We believe the best approach for minimizing the level of deliberate misfueling is making sure operators of 2007 and later model year heavy-duty diesel vehicles are educated about the negative effects on vehicle performance from using diesel fuel with a sulfur level above 15 ppm.

4. Are Additional Requirements Necessary to Address Accidental Misfueling?

There is also the possibility that a truck operator may misfuel accidentally, and not realize they are refueling with the wrong fuel. As noted above, there are a number of reasons a truck operator may find fuel other than 15 ppm sulfur highway diesel fuel when they pull into a retail outlet to refuel. First, the temporary compliance option and hardship provisions will allow refiners to produce two highway diesel fuels during the transition compliance period. Second, there are a number of retail outlets that carry both highway diesel fuel and nonroad diesel fuel at the same location.

With regard to the potential for accidental misfueling of 2007 and later heavy-duty vehicles with 500 ppm sulfur highway diesel fuel during the transition to low sulfur fuel, we believe the labeling requirements described earlier will lower the potential for accidental misfueling. The labels should help vehicle operators identify which fuel is required for their vehicle and help the operator identify the appropriate fuel when they refuel. Although the possibility exists that an operator would not see the fuel pump label and accidentally misfuel with 500 ppm sulfur fuel, we do not believe this will be a common occurrence. Most retail outlets (except truck stops) will likely only carry one grade of highway fuel, and because 15 ppm sulfur fuel is the predominate fuel required even at the start of the program, it will likely be 15 ppm sulfur fuel. Furthermore, the small refiner option lasts for only four years when the number of vehicles needing 15 ppm fuel is relatively small but the majority of fuel out there will be 15 ppm fuel. Last of all, as discussed in Chapter III, Section A.7., a one time misfueling event with 500 ppm fuel will not necessarily irreversibly destroy the emissions control equipment. For these reasons, we believe that a labeling program for both vehicles and fuel pumps will satisfactorily address any concerns over accidental misfueling.

^{ff}“An Analysis of the Factors Leading to the Use of Leaded Gasoline in Automobiles Requiring Unleaded Gasoline,” September 29, 1978, Sobotka & Company, Inc., “Motor Vehicle Tampering Survey – 1983,” July 1984, U.S. EPA, Office of Air and Radiation, and “Anti-Tampering and Anti-Misfueling Programs to Reduce In-Use Emissions From Motor Vehicles,” May 25, 1983 (EPA/AA/83-3). All contained in Docket A-99-06.

With regard to the potential for accidental misfueling with nonroad diesel fuel, few retail outlets currently carry both nonroad and highway diesel fuel. Those retail outlets that do also carry nonroad diesel fuel, the nonroad fuel pump is often located away from the highway fuel pump. Thus, it would be difficult to accidentally misfuel with nonroad diesel fuel. Therefore, we do not believe there will be any significant amount of accidental misfueling of 2007 and later model year heavy-duty diesel vehicles with nonroad diesel fuel. However, as noted earlier, we are requiring that all nonroad fuel pumps at retail outlets carrying both nonroad diesel fuel and highway diesel fuel be labeled. We believe the label requirements are sufficient to address concerns over the potential for misfueling with nonroad diesel fuel.

In summary, for the reasons noted above, we believe that the simple labeling requirements being adopted will help vehicle owners identify and use the correct fuel and will be sufficient to address the level of concern regarding accidental misfueling.

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Chapter V: Economic Impact

A. Economic Impact of the 2007 Model Year Heavy-Duty Diesel Standards

This section contains an analysis of the economic impacts of the emission standards for heavy-duty diesel vehicles. First, a brief outline of the methodology used to estimate the economic impacts is presented, followed by a summary of the technology packages that are expected to be used to meet the standards. Next, the projected costs of the individual technologies are presented, along with a discussion of fixed costs such as research and development (R&D), tooling and certification. Following the discussion of the individual cost components is a summary of the projected per-vehicle cost of the regulations. Finally, an analysis of the aggregate cost for the new engine technologies is presented. Unless noted otherwise all costs presented here are in 1999 dollars.

1. Methodology for Estimating Costs

While the following analysis is based on a relatively uniform emission control strategy for designing the different categories of engines, this is not intended to suggest that a single combination of technologies will actually be used by all manufacturers. In fact, depending on basic engine emission characteristics, EPA expects that emission control technology packages will gradually be fine-tuned to each application. Furthermore, EPA expects manufacturers to use averaging, banking, and trading programs as a means to deploy varying degrees of emission control technologies on different engines. EPA nevertheless believes that the projections presented here provide a cost estimate representative of the different approaches manufacturers are likely to take.

Because many of the technologies which we believe will be used by the industry in order to meet the standards are being applied on a large scale for the first time, we have sought input from a large section of the regulated community, seeking their estimation of the future costs to apply these technologies. Under contract from EPA, ICF Consulting provided surveys to nine engine manufacturers seeking their input on expectations for cost savings which might be enabled through the use of low sulfur diesel fuel and seeking their estimations of the cost and types of emission control technologies which might be applied with low sulfur diesel fuel. Based on responses to these surveys, EPA estimated cost savings to the current and future fleets. The survey responses were also used as the first step in estimating the costs for advanced emission control technologies which may be applied in order to meet the 2007 heavy-duty vehicle

standards.¹ These costs were then further refined by EPA based upon input from members of the Manufacturers of Emission Control Association.

Projected heavy-duty vehicle sale estimates are used in several portions of this analysis. Based on data submitted by engine manufacturers, we estimated 1995 engine sales to be 280,000 for light heavy-duty engines, 140,000 for medium heavy-duty engines, and 220,000 for heavy heavy-duty engines (including those sold into urban bus applications). These numbers are projected to grow at an annual rate of two percent of the base year without compounding through 2035 in this analysis and are included in table V.A-20.²

Costs of control include variable costs (for incremental hardware costs, assembly costs, and associated markups) and fixed costs (for tooling, R&D, and certification). For technologies sold by a supplier to the engine manufacturers, costs are either estimated based upon a direct cost to manufacture the system components plus a 29 percent markup to account for the supplier's overhead and profit, or when available, based upon estimates from suppliers on expected total costs to the manufacturers (inclusive of markups).³ Estimated variable costs for new technologies include a markup to account for increased warranty costs. Variable costs are additionally marked up to account for both manufacturer and dealer overhead and carrying costs. The manufacturer's carrying cost was estimated to be four percent of the direct costs accounting for the capital cost of the extra inventory, and the incremental costs of insurance, handling, and storage. The dealer's carrying cost was marked up three percent reflecting the cost of capital tied up in inventory. This approach to individually estimating manufacturer and dealer markups, to better reflect the value added at each stage of the cycle, was adopted by EPA based upon industry input.⁴

EPA has also identified various factors that will cause cost impacts to decrease over time, making it appropriate to distinguish between near-term and long term costs. Research in the costs of manufacturing has consistently shown that as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts.⁵ The analysis incorporates the effects of this learning curve as described in section A.6 of this chapter. Finally, manufacturers are expected to apply ongoing research to make emission controls more effective and to have lower operating costs over time.

Fixed costs for R&D are assumed to be incurred over the five-year period preceding introduction of the engine, tooling and certification costs are assumed to be incurred one year ahead of initial production. Fixed costs are increased by seven percent for every year before the start of production to reflect the time value of money, and are then recovered with a five-year amortization at the same rate. The analysis also includes consideration of lifetime operating costs where applicable. Projected costs were derived for the four service classes of heavy-duty diesel vehicles listed in Table V.A-1. The cost for each technology applied to urban buses is the

same as the cost of that technology when applied to heavy heavy-duty vehicles, unless specified otherwise.

Table V.A-1. Service Classes of Heavy-Duty Vehicles

<i>Service Class</i>	<i>Vehicle Class</i>	<i>GVWR (lbs.)</i>
Light	2B - 5	8,500 - 19,500
Medium	6 - 7	19,501 - 33,000
Heavy	8	33,001 +
Urban Bus	—	—

2. Heavy-Duty Diesel Technologies for Compliance with the Standards

Several new technologies are projected for complying with the 2007 model year emission standards. We are projecting that NO_x adsorbers and catalyzed diesel particulate filters will be the most likely technologies applied by the industry in order to meet our emissions standards. We also anticipate the introduction of closed crankcase filtration systems for turbocharged heavy-duty diesel engines due to the elimination of the current exception granted to these engines. The fact that manufacturers have several years before implementation of the new standards ensures that the technologies used to comply with the standards will develop significantly before reaching production. This ongoing development will lead to reduced costs in three ways. First, research will lead to enhanced effectiveness for individual technologies, allowing manufacturers to use simpler packages of emission control technologies than we would predict given the current state of development. Similarly, the continuing effort to improve the emission control technologies will include innovations that allow lower-cost production. Finally, manufacturers will focus research efforts on any drawbacks, such as fuel economy impacts or maintenance costs, in an effort to minimize or overcome any potential negative effects.

We anticipate a combination of primary technology upgrades for the 2007 model year. Achieving very low NO_x emissions will require basic research on NO_x emission control technologies and improvements in engine management to take advantage of the aftertreatment system capabilities. The manufacturers are expected to take a systems approach to the problem optimizing the engine and aftertreatment system to realize the best overall performance possible. Since most research to date with aftertreatment technologies has focused on retrofit programs there remains room for significant improvements by taking such a systems approach. We have estimated that the catalyst companies will spend approximately \$220 million to further develop the NO_x and PM/HC control technologies described here. Further we have estimated that the

engine manufacturers will spend approximately \$385 million dollars on R&D to develop the control systems needed to take advantage of the advanced emission control technologies described here. The NO_x adsorber technology in particular is expected to benefit from re-optimization of the engine management system to better match the NO_x adsorber performance characteristics. The majority of the \$385 million dollars we estimated for engine research is expected to be spent on developing this synergy between the engine and NO_x aftertreatment systems. PM/HC control technologies are expected to be less sensitive to engine operating conditions as they have already shown good robustness in retrofit applications with low-sulfur diesel fuel. Nevertheless the manufacturers are expected to take a global systems approach that will optimize operation with consideration to both NO_x and PM/HC emission control subsystems.

EPA contracted with ICF Consulting to 1) Estimate the variable cost for advanced emission control technologies which would be enabled by low sulfur diesel fuel, and 2) Estimate the impacts of low sulfur diesel fuel for engine durability and maintenance costs. Task 1 was completed by Engine, Fuel and Emissions Engineering and is referenced here as “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content, Task 1,” or as the EF&EE cost report. Task 2 was completed by ICF Consulting and is referenced here as “Economic Analysis of Vehicle and Engine Changes Made Possible by the Reduction of Diesel Fuel Sulfur Content, Task 2 - Benefits for Durability and Reduced Maintenance,” or as the ICF low sulfur benefits report.

The results of our cost analysis are considered in the following paragraphs and summarized in Table V.A-2. Technology costs are described in section 3, fixed costs are described in section 4, and maintenance cost savings are described in section 5.

**Table V.A-2. Summary of Near and Long Term Cost Estimates
(net present value in year of sale)**

**Near Term (2007) Light Heavy-Duty Diesel Vehicles
(1999 Dollars per Engine)**

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber System	\$87	\$925	\$0
Catalyzed Diesel Particulate Filter	\$41	\$690	\$55
HC and H ₂ S Clean Up Catalyst	\$0	\$206	\$0
Closed Crankcase System	\$0	\$37	\$31
Low Sulfur Diesel Fuel	\$0	\$0	\$576
Maintenance Savings	\$0	\$0	(\$153)
Total	\$128	\$1,858	\$509

**Long Term (2012+) Light Heavy-Duty Diesel Vehicles
(1999 Dollars per Engine)**

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$0	\$592	\$0
Catalyzed Diesel Particulate Filter	\$0	\$425	\$55
HC and H ₂ S Clean Up Catalyst	\$0	\$132	\$0
Closed Crankcase System	\$0	\$23	\$26
Low Sulfur Diesel Fuel	\$0	\$0	\$609
Maintenance Savings	\$0	\$0	(\$153)
Total	\$0	\$1,172	\$537

Near Term (2007) Medium Heavy-Duty Diesel Vehicles
(1999 Dollars per Engine)

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$231	\$1,080	\$0
Catalyzed Diesel Particulate Filter	\$98	\$852	\$56
HC and H ₂ S Clean Up Catalyst	\$0	\$261	\$0
Closed Crankcase System	\$0	\$42	\$59
Low Sulfur Diesel Fuel	\$0	\$0	\$1,077
Maintenance Savings	\$0	\$0	(\$249)
Total	\$329	\$2,235	\$943

Long Term (2012+) Medium Heavy-Duty Diesel Vehicles
(1999 Dollars per Engine)

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$0	\$691	\$0
Catalyzed Diesel Particulate Filter	\$0	\$527	\$56
HC and H ₂ S Clean Up Catalyst	\$0	\$167	\$0
Closed Crankcase System	\$0	\$27	\$48
Low Sulfur Diesel Fuel	\$0	\$0	\$1,141
Maintenance Savings	\$0	\$0	(\$249)
Total	\$0	\$1,412	\$996

Near Term (2007) Heavy Heavy-Duty Diesel Vehicles
(1999 Dollars per Engine)

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$191	\$1,456	\$0
Catalyzed Diesel Particulate Filter	\$89	\$1,103	\$208
HC and H ₂ S Clean Up Catalyst	\$0	\$338	\$0
Closed Crankcase System	\$0	\$49	\$218
Low Sulfur Diesel Fuel	\$0	\$0	\$3,969
Maintenance Savings	\$0	\$0	(\$610)
Total	\$280	\$2,946	\$3,785

Long Term (2012+) Heavy Heavy-Duty Diesel Vehicles
(1999 Dollars per Engine)

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$0	\$932	\$0
Catalyzed Diesel Particulate Filter	\$0	\$686	\$208
HC and H ₂ S Clean Up Catalyst	\$0	\$216	\$0
Closed Crankcase System	\$0	\$32	\$172
Low Sulfur Diesel Fuel	\$0	\$0	\$4,209
Maintenance Savings	\$0	\$0	(\$610)
Total	\$0	\$1,866	\$3,979

Near Term (2007) Urban Buses
(1999 Dollars per Engine)

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$191	\$1,456	\$0
Catalyzed Diesel Particulate Filter	\$89	\$1,103	\$98
HC and H ₂ S Clean Up Catalyst	\$0	\$338	\$0
Closed Crankcase System	\$0	\$49	\$107
Low Sulfur Diesel Fuel	\$0	\$0	\$4,772
Current Oxidation Catalyst Removed	\$0	(\$338)	\$0
Maintenance Savings	\$0	\$0	(\$352)
Total	\$280	\$2,608	\$4,625

Long Term (2012+) Urban Buses
(1999 Dollars per Engine)

<i>Item</i>	<i>Fixed Cost</i>	<i>Variable Cost</i>	<i>Operating Cost</i>
NOx Adsorber Catalyst	\$0	\$932	\$0
Catalyzed Diesel Particulate Filter	\$0	\$686	\$98
HC and H ₂ S Clean Up Catalyst	\$0	\$216	\$0
Closed Crankcase System	\$0	\$32	\$92
Low Sulfur Diesel Fuel	\$0	\$0	\$4,959
Current Oxidation Catalyst Removed	\$0	(\$216)	\$0
Maintenance Savings	\$0	\$0	(\$352)
Total	\$0	\$1,650	\$4,797

3. Technology/Hardware Costs for Diesel Vehicles and Engines

The following discussion presents the projected costs of the primary technological improvements expected for complying with the emission standards detailing the variable costs of the individual technologies. EPA believes that a small set of technologies integrated into a single emission control system will represent the primary changes manufacturers must make to meet the 2007 model year standards. This integrated system is expected to include elements which could be individually identified as a NO_x adsorber catalyst, a catalyzed diesel particulate filter, a diesel oxidation catalyst, and 15 ppm sulfur diesel fuel to enable the aforementioned emission control technologies. In order to comply with the requirement to eliminate crankcase emissions from all heavy-duty diesel engines, we are projecting the introduction of closed crankcase filtration systems. Lean NO_x catalysts and compact SCR systems were not considered in this analysis, not because the control they offer is an incidental benefit, but because it appears unlikely that they will be part of 2007 model year technology packages.

a. NO_x Adsorber Catalyst Costs

NO_x adsorber catalysts have been developed and are being applied today for stationary power NO_x emission control and for lean burn gasoline engine control. The application of this catalyst technology to diesel engines is relatively new. Therefore we have projected that there will be significant enhancements of the technology in order to better match the characteristics of diesel engines. Nevertheless the basic components of the NO_x adsorber catalyst are well known and include, 1) an oxidation catalyst, typically platinum, 2) an alkaline earth metal to store NO_x, typically barium, 3) a NO_x reduction catalyst, typically rhodium, and 4) a substrate and can to hold and support the catalyst washcoat. Cost estimates for the NO_x adsorber catalysts in 2007 are presented in Table V.A-3 below.

The material costs listed in Table V.A-3 represent costs to the engine manufacturers inclusive of supplier markups. The total direct cost to the manufacturer includes an estimate of warranty costs for the NO_x adsorber system. Hardware costs are additionally marked up to account for both manufacturer and dealer overhead and carrying costs. The manufacturer's carrying cost was estimated to be four percent of the direct costs accounting for the capital cost of the extra inventory, and the incremental costs of insurance, handling, and storage. The dealer's carrying cost was marked up three percent reflecting the cost of capital tied up in inventory. This approach to individually estimating manufacturer and dealer markups, to better reflect the value added at each stage of the cycle, was adopted by EPA based upon industry input.⁶

We have estimated the cost of this system based on information from the following reports:

1. Estimated Economic Impact of New Emission Standards for Heavy-Duty On-Highway Engines, March 1997, EPA 420-R-97-009.
2. Cost Estimates for Heavy-Duty Gasoline Vehicles, September 1998, EPA Air Docket A-99-06 Item No. II-A-13.
3. Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content, December 1999, Air Docket A-99-06.

The individual assumptions used to estimate the cost for the system are documented in the following subsections.

Catalyst Volume

The Engine Manufacturers Association was asked as part of a contractor work assignment to gather input from their members on likely technology solutions including the NOx adsorber catalyst.⁷ The respondents indicated that the catalyst volume for a NOx adsorber catalyst could range from 1.5 times the engine displacement to as much as 2.5 times the engine displacement based on today's washcoating technology. Based on current lean burn gasoline catalyst designs and engineering judgement we have estimated that the NOx adsorber catalyst will be sized on average 1.5 times the engine displacement.

Substrate Cost

The ceramic flow through substrates used for the NOx adsorber catalyst are estimated to cost approximately \$5 per liter. This cost estimate is based upon the relationship developed for current heavy-duty gasoline catalyst substrates as documented in Cost Estimates for Heavy-Duty Gasoline Vehicles of

$$C = \$4.67 \times V + \$1.50$$

where:

C = cost to the vehicle manufacturer from the substrate supplier

V = substrate volume in liters.

Washcoating and Canning

The report entitled, "Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content," estimates a "value-added" engineering and material product, called washcoating and canning, based on feedback from members of the Manufacturers of Emission Control Association (MECA). By using a value added component that accounts for fixed costs (including R&D), overhead, marketing and profits from likely suppliers of the technology, we can estimate this fraction of the cost for the technology apart

from the other components which are typically more widely available as commodities (e.g., precious metals and catalyst substrates). Here, we have taken the washcoating and canning costs estimated in the above mentioned report and have split out 11 percent of that cost for R&D, with the remaining 89 percent continuing to be called washcoat and canning. The R&D fraction is then used to estimate a total R&D expenditure for the industry due to the 2007 HD rule of \$133 million recovered over the first five years of the program. We arrived at a value of 11 percent for R&D by looking at R&D costs as a fraction of gross profits from the annual report of one of the larger catalyst manufacturers.

Precious Metals

The total precious metal content for the NO_x adsorber is estimated to be 50 g/ft³ with platinum representing 90% of that total and Rhodium 10%. The costs for rhodium and platinum are the same as estimated in the Tier 2 RIA (EPA420-99-023) and are \$868/troy oz. for rhodium and \$412 / troy oz. for platinum.

Barium

The cost for barium carbonate (the primary NO_x storage material) is assumed to be less than \$1 per catalyst as estimated in “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content.”

Can Housing

The material cost for the can housing is estimated based on the catalyst volume plus 20% for transition cones, plus 20% for scrappage (material purchased but unused in the final product) and a price of \$.98/lb for 16 gauge stainless steel as estimated in contractor report “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content.” The resulting material costs are summarized in the table below.

NO_x Regeneration System

The NO_x regeneration system is likely to include a NO_x/O₂ sensor, a means for exhaust air to fuel ratio control (one or more exhaust fuel injectors or in-cylinder means), a temperature sensor and possibly a means to control mass flow through a portion of the catalyst system (a “dual-bed” system). The cost for such a system is \$300 for light and medium heavy-duty vehicles and \$350 for heavy heavy-duty vehicles as estimated in contractor report “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content.”

Direct Labor Costs

The direct labor costs for the catalyst are estimated based upon an estimate of the number of hours required for assembly and established labor rates. Additional overhead for labor was estimated as 40 percent of the labor rate.⁸

Warranty Costs

We have estimated the warranty costs based upon a 1% claim rate, and an estimate of parts and labor costs per incident. The labor rate is assumed to be \$50 per hour, and a parts cost are estimated as 2.5 times the OEM component cost. These costs are summarized in the NOx absorber summary table below.

Manufacturer and Dealer Carrying Costs

The manufacturer's carrying cost was estimated at 4% of the direct costs. This reflects primarily the costs of capital tied up in extra inventory, and secondarily the incremental costs of insurance, handling and storage. The dealer's carrying cost was estimated at 3% of the incremental cost, again reflecting primarily the cost of capital tied up in extra inventory.

Summary - Total System Estimate

Table V.A-3. 2007 NOx Adsorber Cost Estimate

<i>NOx Adsorber Catalyst</i>	<i>Vehicle Class</i>		
	<i>LHDD</i>	<i>MHDD</i>	<i>HHDD</i>
Catalyst Volume	9	12	20
Material Cost			
Substrate	\$47	\$63	\$103
Washcoat (value added engineering)	\$223	\$267	\$312
Platinum	\$189	\$253	\$411
Rhodium	\$44	\$59	\$96
Alkaline Earth Oxide	\$1	\$1	\$1
Can Housing	\$9	\$13	\$17
NOx Regeneration System	\$300	\$300	\$350
Direct Labor Costs	\$37	\$37	\$49
Total Direct Cost to Mfr.	\$851	\$992	\$1,339
Warranty Costs (1% Claim Rate)	\$22	\$26	\$34
Mfr. Carrying Cost	\$26	\$30	\$40
Total Cost to Dealer	\$899	\$1,048	\$1,413
Dealer Carrying Cost	\$27	\$31	\$42
Total Cost to Customer	\$925	\$1,080	\$1,456

b. Catalyzed Diesel Particulate Filter Costs

Catalyzed diesel particulate filters are already in limited production for retrofits in markets where low sulfur diesel fuel is available. The final design configurations and catalyst compositions that these technologies are likely to have in 2007 can be estimated with some accuracy. Based on current systems and input from industry, costs for catalyzed diesel particulate filters in 2007 were estimated and are presented in Table V.A-4 below. These costs are reduced here by \$45 for light heavy-duty vehicles, \$50 for medium heavy-duty vehicles and \$55 for heavy heavy-duty vehicles to reflect the fact that diesel particulate filters also serve the function of a muffler, eliminating the need for that device.

Material costs for the catalyzed diesel particulate filter given here are inclusive of supplier markups as they reflect the expected cost to the engine manufacturer to purchase the

hardware from a supplier. The total direct cost to the manufacturer includes an estimate of warranty costs for the catalyzed diesel particulate filter. Hardware costs are additionally marked up to account for both manufacturer and dealer overhead and carrying costs. The manufacturer's carrying cost was estimated to be four percent of the direct costs accounting for the capital cost of the extra inventory, and the incremental costs of insurance, handling, and storage. The dealer's carrying cost gives a three percent markup reflecting the cost of capital tied up in inventory. This approach to individually estimating manufacturer and dealer markups, to better reflect the value added at each stage of the cycle, was adopted by EPA based upon industry input.⁹

Diesel Particulate Filter Volume

The Engine Manufacturers Association was asked as part of a contractor work assignment to gather input from their members on catalyzed diesel particulate filters for heavy-duty applications.¹⁰ The respondents indicated that the particulate filter volume could range from 1.5 times the engine displacement to as much as 2.5 times the engine displacement based on today's experiences with cordierite filter technologies. The size of the diesel particulate filter is selected largely based upon the maximum allowable flow restriction for the engine. Generically the filter size is inversely proportional to its resistance to flow (a larger filter is less restrictive than a similar smaller filter). We have estimated that the diesel particulate filter will be sized to be 1.5 times the engine displacement in 2007 based on these responses and on-going research aimed at improving filter porosity control to give a better trade-off between flow restrictions and filtering efficiency.

Diesel Particulate Filter Costs

Cost estimates for cordierite diesel particulate filters (the most common type used today) were provided by several members of the Manufacturers of Emission Control Association (MECA) for each vehicle class. The cost estimates showed a non-linear relationship with particulate filter size with larger filters being somewhat less expensive per liter of filter volume. Here we have used an average of the MECA provided cost estimates for each of the classes to arrive at our cost estimate.^a

^a MECA member companies provided estimates of future cordierite filter costs to EPA's contractor EF&EE. EF&EE estimated the cost of future filters with a linear fit to the estimates provided. In this analysis, we have estimated the future cost of the cordierite filters by averaging the MECA member estimates for each vehicle class, rather than using the contractor's linear fit estimate. We used this alternate approach for estimating the cost of the cordierite filter due to the non-linear nature of the cost estimates provided by MECA. This change from the contractor's estimate increases the cost for light heavy-duty vehicles while decreasing the cost for heavy heavy-duty vehicles due to the non-linear nature of the cost estimates. The MECA estimates were identified as Confidential Business Information when provided to EF&EE and are therefore not provided in the docket associated with this RIA.

Washcoating and Canning

Washcoating and canning costs are estimated and accrued in the same manner as for the NO_x adsorber technology discussed above. The resulting variable costs for washcoating and canning are \$134 for light heavy-duty DPFs, \$178 for medium heavy-duty DPFs, and \$223 for heavy heavy-duty DPFs. Per filter R&D costs were estimated in the same manner as described above for the NO_x adsorber catalyst and are estimated to be \$16, \$22, and \$27 for diesel particulate filters applied to light, medium and heavy heavy-duty vehicles respectively. Aggregating these R&D costs over the projected engine volumes during the first five years of the program allows us to estimate the total R&D expense for catalyzed diesel particulate filters as \$87 million.

Precious Metals

The total precious metal content for catalyzed diesel particulate filters is estimated to be 30 g/ft³ with platinum as the only precious metal used in the filter. The cost for platinum is the same as estimated in the Tier 2 RIA (EPA420-99-023) and is \$412/troy ounce.

Can Housing

The material cost for the can housing is estimated based on the filter volume plus 20% for transition cones, plus 20% for scrappage and a price of \$.98/lb for 16 gauge stainless steel as estimated in contractor report “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content.” The resulting material costs are summarized in the table below.

Differential Pressure Sensor

We have assumed that the catalyzed diesel particulate filter system will require the use of a differential pressure sensor to provide a diagnostic monitoring function of the filter. A cost of \$45 per sensor has been assumed as estimated in contractor report “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content.”

Direct Labor Costs

The direct labor costs for the catalyzed diesel particulate filter are estimated in contractor report “Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction of Diesel Fuel Sulfur Content” based upon an estimate of the number of hours required for assembly and established labor rates.

Warranty Costs

We have estimated the warranty costs based upon a 1% claim rate, and an estimate of parts and labor costs per incident. The labor rate is assumed to be \$50 per hour, and a parts cost are estimated as 2.5 times the OEM component cost. These costs are summarized in the catalyzed diesel particulate filter summary table below.

Manufacturer and Dealer Carrying Costs

The manufacturer's carrying cost was estimated at 4% of the direct costs. This reflects primarily the costs of capital tied up in extra inventory, and secondarily the incremental costs of insurance, handling and storage. The dealer's carrying cost was estimated at 3% of the incremental cost, again reflecting primarily the cost of capital tied up in extra inventory.

Muffler Costs

The diesel particulate filter costs are reduced here by \$45 for light heavy-duty vehicles, \$50 for medium heavy-duty vehicles and \$55 for heavy heavy-duty vehicles to reflect the fact that diesel particulate filters also serve the function of a muffler, eliminating the need for that device.

Summary - Total System Estimate

Table V.A-4. 2007 Catalyzed Diesel Particulate Filter Cost Estimate

<i>Catalyzed Diesel Particulate Filter</i>	<i>Vehicle Class</i>		
	<i>LHDD</i>	<i>MHDD</i>	<i>HHDD</i>
Trap Volume (liters)	9	12	20
Material Cost			
Filter Trap	\$300	\$360	\$420
Washcoat (value added engineering)	\$134	\$178	\$223
Platinum	\$126	\$168	\$274
Can Housing	\$7	\$10	\$14
Differential Pressure Sensor	\$45	\$45	\$45
Direct Labor Costs	\$49	\$49	\$62
Total Direct Cost to Mfr.	\$670	\$822	\$1,056
Warranty Costs (1% Claim Rate)	\$16	\$20	\$25
Mfr. Carrying Cost	\$27	\$33	\$42
Total Cost to Dealer	\$713	\$875	\$1,124
Dealer Carrying Cost	\$21	\$26	\$34
Savings by removing muffler	(\$45)	(\$50)	(\$55)
Total Cost to Customer	\$690	\$851	\$1,103

c. Diesel Oxidation Catalyst (HC and H₂S “Clean-Up” Catalyst)

The NO_x adsorber regeneration and desulfation functions may produce undesirable by-products in the form of momentary increases in HC emissions or in odorous hydrogen sulfide (H₂S) emissions. In order to control these potential products we have assumed that manufacturers may choose to apply a diesel oxidation catalyst (DOC) downstream of the NO_x adsorber technology. The DOC would serve a “clean-up” function to oxidize any HC and H₂S emissions to more desirable products as outlined in Chapter 3.

We have estimated the cost of diesel oxidation catalysts below in Table V.A-5 as \$206 for a light heavy-duty diesel vehicle, \$261 for a medium heavy-duty diesel vehicle and \$338 for a heavy heavy-duty diesel vehicle. The individual component costs for the DOC were estimated in the same manner as for the NO_x adsorber and CDPF above.

Table V.A-5. 2007 Diesel Oxidation Catalyst Cost Estimate

<i>Catalyzed Diesel Particulate Filter</i>	<i>Vehicle Class</i>		
	<i>LHDD</i>	<i>MHDD</i>	<i>HHDD</i>
Catalyst Volume (liters)	6	8	13
Material Cost			
Substrate	\$32	\$42	\$69
Washcoat (value added engineering)	\$125	\$150	\$175
Platinum (5 g/ft ³)	\$14	\$19	\$30
Can Housing	\$4	\$6	\$9
Direct Labor Costs	\$13	\$13	\$13
Total Direct Cost to Mfr.	\$187	\$237	\$308
Warranty Costs (1% Claim Rate)	\$5	\$6	\$8
Mfr. Carrying Cost	\$7	\$9	\$12
Total Cost to Dealer	\$200	\$253	\$328
Dealer Carrying Cost	\$6	\$8	\$10
Total Cost to Customer	\$206	\$261	\$338

d. Closed Crankcase Filtration Systems

New engines introduced in Europe in the 2000 model year must have closed crankcases as part of the EURO III emission standards. The most common technology solution to this requirement is a closed crankcase filtration system which separates oil and other contaminants from the blow-by gases and then routes the blow-by gases into the engines intake system downstream of the air filter. An analysis of this type of control system was made as part of the 2004 heavy-duty rulemaking and system costs were estimated.¹¹ We have estimated the new vehicle cost of this type of closed crankcase system in Table V.A-6.

Table V.A-6. 2007 Closed Crankcase Filtration System Cost Estimate¹²

<i>Closed Crankcase Filtration</i>	<i>Vehicle Class</i>		
	<i>LHDD</i>	<i>MHDD</i>	<i>HHDD</i>
Hardware Costs			
Filter Housing	\$10	\$12	\$15
Service Filter (30,000 mile interval)	\$10	\$12	\$15
PCV Valve	\$5	\$5	\$5
Tubing (plumbing)	\$2	\$2	\$2
Assembly	\$1	\$1	\$1
Total Variable Cost to Manufacturer	\$28	\$32	\$38
Markup (@ 29%)	\$8	\$9	\$11
Total CCV RPE	\$37	\$42	\$49

Additionally there is a recurring cost for this type of system associated with the replacement of a service filter on a 30,000 mile interval. The cost for the service filter is estimated to be \$10, \$12, and \$15 for light, medium, and heavy heavy-duty vehicles respectively. These operating costs are summarized in section 5 below along with other diesel vehicle operating costs.

4. Fixed Costs

Fixed costs are costs to the manufacturer which are non-recurring and include costs for research and development, tooling and new engine certification. The fixed costs for the diesel control portion of this rulemaking are given below. Expected expenditures are reported in the year incurred as non-annualized costs for PM/HC and NOx control separately. In general fixed costs are incurred prior to the introduction of the new vehicles and are assumed to be recovered over a five year period beginning with the first year of vehicle sale. Fixed costs are increased by seven percent for every year before the start of production to reflect the time value of money. The assumed recovery values for fixed costs associated with NOx and PM/HC control are given in the tables as annualized values.

a. Research and Development

The advanced emission control technologies which are likely to be applied in 2007 are already relatively well developed and are seeing application in retrofit markets where low sulfur diesel fuel is available or in other fields, such as power generation. Further development of these

catalyst technologies to better adapt them to diesel applications is still needed however. We have estimated, based on current industry practices, that expenditures to further develop these advanced emission control technologies by the catalyst suppliers will be approximately \$87 million for the CDPF technology and \$133 million for the NO_x adsorber technology (see description of these estimates section V.A.3.a and V.A.3.b above for each of these technologies).

Developing the integrated electronic engine control systems required to take advantage of these new emission reduction technologies for diesel engines will be a significant challenge for the diesel engine manufacturers. This is a large task which will entail complete re-optimization of diesel engine operation away from minimizing engine out emissions to minimizing total system emissions. In addition the manufacturers will need to develop a full understanding of the long term durability of the total emission control system in order to ensure compliance over the useful life of the vehicle and in order to develop deterioration factors (DFs) for the systems. We have therefore estimated that each of the 11 major diesel engine manufacturers will invest approximately \$7 million per year on research and development over a period of five years to adapt their engine technology to the advanced emission control technologies described here. Seven million dollars represents the approximate cost for a team of more than 21 engineers and 28 technicians to carry out advanced engine research, including the cost for engine test cell time and prototype system fabrication. In total we have estimated that the engine manufacturers will spend approximately \$385 million on R&D. Although we believe the manufacturers will take a total system approach optimizing the engine control system for PM/HC control and for NO_x control concurrently, we have apportioned these research dollars separately for NO_x and PM/HC due to the more complicated changes required to enable the NO_x adsorber technology. We have apportioned 25 percent of the \$385 million estimated for engine R&D to PM/HC control and the remaining 75 percent for development of the systems required for NO_x control. These R&D costs are further apportioned between each vehicle classes based on the ratio of the number of engine families in a vehicle weight class to the total number of heavy duty diesel engine families.

The R&D costs for the advanced PM/HC emission control technologies are assumed to be incurred over the five year period from 2002 through 2006 and then recovered over the five year period starting in 2007. Research and development costs for the NO_x adsorber system are assumed to be incurred in ratio to the NO_x standard phase-in timetable and as such are spread over an eight year period beginning in 2002. For the vehicles introduced as part of the 50 percent NO_x phase-in in 2007 these costs are assumed to be accrued in the five years preceding 2007 and to be fully recovered by 2011.

Tables V.A-7, V.A-8, and V.A-9 provide a year by year breakdown of the annualized and non-annualized costs for research and development for the light, medium and heavy heavy-duty vehicle categories. Fixed costs for urban buses are included in the cost estimates for heavy heavy-duty vehicles.

Table V.A-7. Annualized and Non-Annualized R&D Costs for Light Heavy-Duty Diesel Engines

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
<i>Year</i>	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2002	0	0	\$9,420,675	\$0	\$0	\$10,300,813	\$0	\$0
2003	0	0	\$9,420,675	\$0	\$0	\$10,300,813	\$0	\$0
2004	0	0	\$9,420,675	\$0	\$0	\$10,300,813	\$0	\$0
2005	0	0	\$9,420,675	\$0	\$0	\$20,601,625	\$0	\$0
2006	0	0	\$9,420,675	\$0	\$0	\$20,601,625	\$0	\$0
2007	341,000	170,500	\$0	\$13,212,984	\$39	\$10,300,813	\$14,447,422	\$85
2008	346,600	173,300	\$0	\$13,212,984	\$38	\$10,300,813	\$14,447,422	\$83
2009	352,200	176,100	\$0	\$13,212,984	\$38	\$10,300,813	\$14,447,422	\$82
2010	357,800	357,800	\$0	\$13,212,984	\$37	\$0	\$28,894,845	\$81
2011	363,400	363,400	\$0	\$13,212,984	\$36	\$0	\$28,894,845	\$80
2012	369,000	369,000	\$0	\$0	\$0	\$0	\$14,447,422	\$78
2013	374,600	374,600	\$0	\$0	\$0	\$0	\$14,447,422	\$77
2014	380,200	380,200	\$0	\$0	\$0	\$0	\$14,447,422	\$76
2015	385,800	385,800	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-8. Annualized and Non-Annualized R&D Costs for Medium Heavy-Duty Diesel Engines

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2002	0	0	\$11,161,150	\$0	\$0	\$13,811,325	\$0	\$0
2003	0	0	\$11,161,150	\$0	\$0	\$13,811,325	\$0	\$0
2004	0	0	\$11,161,150	\$0	\$0	\$13,811,325	\$0	\$0
2005	0	0	\$11,161,150	\$0	\$0	\$27,622,650	\$0	\$0
2006	0	0	\$11,161,150	\$0	\$0	\$27,622,650	\$0	\$0
2007	173,600	86,800	\$0	\$15,654,090	\$90	\$13,811,325	\$19,371,098	\$223
2008	176,400	88,200	\$0	\$15,654,090	\$89	\$13,811,325	\$19,371,098	\$220
2009	179,200	89,600	\$0	\$15,654,090	\$87	\$13,811,325	\$19,371,098	\$216
2010	182,000	182,000	\$0	\$15,654,090	\$86	\$0	\$38,742,196	\$213
2011	184,800	184,800	\$0	\$15,654,090	\$85	\$0	\$38,742,196	\$210
2012	187,600	187,600	\$0	\$0	\$0	\$0	\$19,371,098	\$207
2013	190,400	190,400	\$0	\$0	\$0	\$0	\$19,371,098	\$203
2014	193,200	193,200	\$0	\$0	\$0	\$0	\$13,371,098	\$201
2015	196,000	196,000	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-9. Annualized and Non-Annualized R&D Costs for Heavy Heavy-Duty Diesel Engines and Urban Buses

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
<i>Year</i>	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2002	0	0	\$16,165,875	\$0	\$0	\$18,102,013	\$0	\$0
2003	0	0	\$16,165,875	\$0	\$0	\$18,102,013	\$0	\$0
2004	0	0	\$16,165,875	\$0	\$0	\$18,102,013	\$0	\$0
2005	0	0	\$16,165,875	\$0	\$0	\$36,204,025	\$0	\$0
2006	0	0	\$16,165,875	\$0	\$0	\$36,024,025	\$0	\$0
2007	272,800	136,400	\$0	\$22,673,476	\$83	\$18,102,013	\$25,389,009	\$186
2008	277,200	138,600	\$0	\$22,673,476	\$82	\$18,102,013	\$25,389,009	\$183
2009	281,600	140,800	\$0	\$22,673,476	\$81	\$18,102,013	\$25,389,009	\$180
2010	286,000	286,000	\$0	\$22,673,476	\$79	\$0	\$50,778,018	\$178
2011	290,400	290,400	\$0	\$22,673,476	\$78	\$0	\$50,778,018	\$175
2012	294,800	294,800	\$0	\$0	\$0	\$0	\$25,389,009	\$172
2013	299,200	299,200	\$0	\$0	\$0	\$0	\$25,389,009	\$170
2014	303,600	303,600	\$0	\$0	\$0	\$0	\$25,389,009	\$167
2015	308,000	308,000	\$0	\$0	\$0	\$0	\$0	\$0

b. Tooling Costs

Capital costs for new, or changes to existing machine tooling, required to produce new engines to meet the standard are a fixed cost and are assumed to be incurred one year prior to the introduction of a new vehicle meeting the emission standard. The cost for the advanced aftertreatment systems, the NOx adsorber and catalyzed diesel particulate filter, discussed in section V.A.3 have been estimated based on cost to the engine manufacturer and are therefore inclusive of tooling cost to manufacture those items. Changes to the electronic control system and to the fuel and air management systems on the diesel engine may lead to some changes in tooling cost which are accounted for here. These systems are themselves expected to use the same hardware components developed to meet the 2004 heavy duty engine emission standards. Some changes may be necessary however, to accommodate the advanced aftertreatment systems described here. These changes are not expected to change the cost of the hardware itself in an appreciable way, but some tooling changes may be required. Since these tooling costs are intended to account for engine changes to the electronic control system and to the fuel and air management systems of the engine similar to those required for the Phase 1 standards, we have used the same tooling estimate for the Phase 2 engines here. These possible tooling costs have

been estimated to be approximately \$6 million for light heavy-duty engines, \$9 million for medium heavy-duty engines, and \$10 million for heavy heavy-duty engines and urban buses.¹³

The tooling costs have been apportioned evenly between NOx and PM/HC control technologies as these system changes are likely to be made based on optimizations for both types of aftertreatment system. The tooling charges apportioned for the NOx control technologies are assumed to occur in two equal steps sequenced with the phase-in period of the NOx standard. The tooling costs for each vehicle weight class are given in Tables V.A-10, V.A-11, and V.A-12.

Table V.A-10. Annualized and Non-Annualized Tooling Costs for Light Heavy-Duty Diesel Engines

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2005	0	0	\$0	\$0	\$0	\$0	\$0	\$0
2006	0	0	\$2,775,000	\$0	\$0	\$1,387,500	\$0	\$0
2007	341,000	170,500	\$0	\$724,172	\$2	\$0	\$362,086	\$2
2008	346,600	173,300	\$0	\$724,172	\$2	\$0	\$362,086	\$2
2009	352,200	176,100	\$0	\$724,172	\$2	\$1,387,500	\$362,086	\$2
2010	357,800	357,800	\$0	\$724,172	\$2	\$0	\$724,172	\$2
2011	363,400	363,400	\$0	\$724,172	\$2	\$0	\$724,172	\$2
2012	369,000	369,000	\$0	\$0	\$0	\$0	\$362,086	\$2
2013	374,600	374,600	\$0	\$0	\$0	\$0	\$362,086	\$2
2014	380,200	380,200	\$0	\$0	\$0	\$0	\$362,086	\$2
2015	385,800	385,800	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-11. Annualized and Non-Annualized Tooling Costs for Medium Heavy-Duty Diesel Engines

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
<i>Year</i>	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2005	0	0	\$0	\$0	\$0	\$0	\$0	\$0
2006	0	0	\$4,443,000	\$0	\$0	\$2,443,650	\$0	\$0
2007	173,600	86,800	\$0	\$1,159,459	\$7	\$0	\$637,702	\$7
2008	176,400	88,200	\$0	\$1,159,459	\$7	\$0	\$637,702	\$7
2009	179,200	89,600	\$0	\$1,159,459	\$6	\$2,443,650	\$637,702	\$7
2010	182,000	182,000	\$0	\$1,159,459	\$6	\$0	\$1,275,405	\$7
2011	184,800	184,800	\$0	\$1,159,459	\$6	\$0	\$1,275,405	\$7
2012	187,600	187,600	\$0	\$0	\$0	\$0	\$637,702	\$7
2013	190,400	190,400	\$0	\$0	\$0	\$0	\$637,702	\$7
2014	193,200	193,200	\$0	\$0	\$0	\$0	\$637,702	\$7
2015	196,000	196,000	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-12. Annualized and Non-Annualized Tooling Costs for Heavy Heavy-Duty Diesel Engines and Urban Buses

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
<i>Year</i>	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2005	0	0	\$0	\$0	\$0	\$0	\$0	\$0
2006	0	0	\$5,132,750	\$0	\$0	\$2,566,375	\$0	\$0
2007	272,800	136,400	\$0	\$1,339,458	\$5	\$0	\$669,729	\$5
2008	277,200	138,600	\$0	\$1,339,458	\$5	\$0	\$669,729	\$5
2009	281,600	140,800	\$0	\$1,339,458	\$5	\$2,566,375	\$669,729	\$5
2010	286,000	286,000	\$0	\$1,339,458	\$5	\$0	\$1,339,458	\$5
2011	290,400	290,400	\$0	\$1,339,458	\$5	\$0	\$1,339,458	\$5
2012	294,800	294,800	\$0	\$0	\$0	\$0	\$669,729	\$5
2013	299,200	299,200	\$0	\$0	\$0	\$0	\$669,729	\$4
2014	303,600	303,600	\$0	\$0	\$0	\$0	\$669,729	\$4
2015	308,000	308,000	\$0	\$0	\$0	\$0	\$0	\$0

c. Certification Costs

Manufacturers will also incur costs to certify the range of engine families to the emission standards. EPA previously developed a methodology for calculating certification costs which results in an estimated certification cost of \$30,000 per engine family.¹⁴ Here we have assumed that all engine families will require certification in 2007 with the introduction of the new PM and HC standards. Additionally as engine families are phased-in to meet the new NOx standards they will again require certification. We have assumed that in the first year of the NOx phase-in period 100 percent of the engine families will require certification and that in the fourth year of the phase (when 100 percent are phased in) that 50 percent of the engine families will require certification.

The total cost for certifying engines under this program can be rounded up to \$5 million. Distributing those costs across the different engine categories, amortizing the costs over five years, and dividing by the number of projected sales for each category results in per-engine costs between \$1 and \$3 for each category of heavy-duty diesel vehicles. These costs are detailed in Tables V.A-13, V.A-14, and V.A-15 for each of the heavy-duty vehicle weight classes.

Table V.A-13. Annualized and Non-Annualized Certification Costs for Light Heavy-Duty Diesel Engines

<i>Calendar</i>	<i>Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2005	0	0	\$0	\$0	\$0	\$0	\$0	\$0
2006	0	0	\$480,000	\$0	\$0	\$0	\$0	\$0
2007	341,000	170,500	\$0	\$125,262	\$0.4	\$0	\$0	\$0
2008	346,600	173,300	\$0	\$125,262	\$0.4	\$0	\$0	\$0
2009	352,200	176,100	\$0	\$125,262	\$0.4	\$240,000	\$0	\$0
2010	357,800	357,800	\$0	\$125,262	\$0.4	\$0	\$62,631	\$0.3
2011	363,400	363,400	\$0	\$125,262	\$0.3	\$0	\$62,631	\$0.3
2012	369,000	369,000	\$0	\$0	\$0	\$0	\$62,631	\$0.3
2013	374,600	374,600	\$0	\$0	\$0	\$0	\$62,631	\$0.3
2014	380,200	380,200	\$0	\$0	\$0	\$0	\$62,631	\$0.3
2015	385,800	385,800	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-14. Annualized and Non-Annualized Certification Costs for Medium Heavy-Duty Diesel Engines

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
<i>Year</i>	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2005	0	0	\$0	\$0	\$0	\$0	\$0	\$0
2006	0	0	\$1,020,000	\$0	\$0	\$0	\$0	\$0
2007	173,600	86,800	\$0	\$266,182	\$1.5	\$0	\$0	\$0
2008	176,400	88,200	\$0	\$266,182	\$1.5	\$0	\$0	\$0
2009	179,200	89,600	\$0	\$266,182	\$1.5	\$510,000	\$0	\$0
2010	182,000	182,000	\$0	\$266,182	\$1.5	\$0	\$133,091	\$1.5
2011	184,800	184,800	\$0	\$266,182	\$1.4	\$0	\$133,091	\$1.4
2012	187,600	187,600	\$0	\$0	\$0	\$0	\$133,091	\$1.4
2013	190,400	190,400	\$0	\$0	\$0	\$0	\$133,091	\$1.4
2014	193,200	193,200	\$0	\$0	\$0	\$0	\$133,091	\$1.4
2015	196,000	196,000	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-15. Annualized and Non-Annualized Certification Costs for Heavy Heavy-Duty Diesel Engines and Urban Buses

<i>Calendar</i>	<i>Projected Vehicle Sales</i>		<i>PM/HC Control</i>			<i>NOx Control</i>		
<i>Year</i>	<i>meeting PM/HC Std</i>	<i>meeting NOx Std</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>	<i>non-annualized</i>	<i>annualized</i>	<i>ann. per vehicle</i>
2005	0	0	\$0	\$0	\$0	\$0	\$0	\$0
2006	0	0	\$1,200,000	\$0	\$0	\$0	\$0	\$0
2007	272,800	136,400	\$0	\$313,156	\$1.2	\$0	\$0	\$0
2008	277,200	138,600	\$0	\$313,156	\$1.1	\$0	\$0	\$0
2009	281,600	140,800	\$0	\$313,156	\$1.1	\$600,000	\$0	\$0
2010	286,000	286,000	\$0	\$313,156	\$1.1	\$0	\$156,578	\$1.1
2011	290,400	290,400	\$0	\$313,156	\$1.1	\$0	\$156,578	\$1.1
2012	294,800	294,800	\$0	\$0	\$0	\$0	\$156,578	\$1.1
2013	299,200	299,200	\$0	\$0	\$0	\$0	\$156,578	\$1.1
2014	303,600	303,600	\$0	\$0	\$0	\$0	\$156,578	\$1.0
2015	308,000	308,000	\$0	\$0	\$0	\$0	\$0	\$0

d. Summary of Fixed Costs

The total annualized fixed costs are summarized here for light, medium and heavy heavy-duty vehicles. Fixed costs for urban buses are included in the estimates for heavy heavy-duty diesel vehicles. Research and Development costs account for over 90 percent of the total fixed costs per engine in our analysis. Tables V.A-16, V.A-17 and V.A-18 below summarize fixed costs in each year of the program.

Table V.A-16. Annualized Fixed Costs for Light Heavy-Duty Diesel Engines

Calendar	Projected Vehicle Sales		PM/HC Control		NOx Control		Total	
	meeting PM/HC Std	meeting NOx Std	annualized	annualized per vehicle	annualized	annualized per vehicle	annualized	annualized per vehicle
2007	341,000	170,500	\$14,062,419	\$41	\$14,809,509	\$87	\$28,871,92	\$128
2008	346,600	173,300	\$14,062,419	\$41	\$14,809,509	\$85	\$28,871,92	\$126
2009	352,200	176,100	\$14,062,419	\$40	\$14,809,509	\$84	\$28,871,92	\$124
2010	357,800	357,800	\$14,062,419	\$39	\$29,681,648	\$83	\$43,744,06	\$122
2011	363,400	363,400	\$14,062,419	\$39	\$29,681,648	\$82	\$43,744,06	\$121
2012	369,000	369,000	\$0	\$0	\$14,872,140	\$81	\$14,872,14	\$81
2013	374,600	374,600	\$0	\$0	\$14,872,140	\$79	\$14,872,14	\$79
2014	380,200	380,200	\$0	\$0	\$14,872,140	\$78	\$14,872,14	\$78
2015	385,800	385,800	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-17. Annualized Fixed Costs for Medium Heavy-Duty Diesel Engines

Calendar	Projected Vehicle Sales		PM/HC Control		NOx Control		Total	
	meeting PM/HC Std	meeting NOx Std	annualized	annualized per vehicle	annualized	annualized per vehicle	annualized	annualized per vehicle
2007	173,600	86,800	\$17,079,731	\$98	\$20,008,800	\$231	\$37,088,531	\$329
2008	176,400	88,200	\$17,079,731	\$97	\$20,008,800	\$227	\$37,088,531	\$324
2009	179,200	89,600	\$17,079,731	\$95	\$20,008,800	\$223	\$37,088,531	\$318
2010	182,000	182,000	\$17,079,731	\$94	\$40,150,691	\$221	\$57,230,422	\$315
2011	184,800	184,800	\$17,079,731	\$92	\$40,150,691	\$217	\$57,230,422	\$309
2012	187,600	187,600	\$0	\$0	\$20,141,891	\$215	\$20,141,891	\$215
2013	190,400	190,400	\$0	\$0	\$20,141,891	\$212	\$20,141,891	\$212
2014	193,200	193,200	\$0	\$0	\$20,141,891	\$209	\$20,141,891	\$209
2015	196,000	196,000	\$0	\$0	\$0	\$0	\$0	\$0

Table V.A-18. Annualized Fixed Costs for Heavy Heavy-Duty Diesel Engines and Urban Buses

Calendar	Projected Vehicle Sales		PM/HC Control		NOx Control		Total	
Year	meeting PM/HC Std	meeting NOx Std	annualized	annualized per vehicle	annualized	annualized per vehicle	annualized	annualized per vehicle
2007	272,800	136,400	\$24,326,090	\$89	\$26,058,738	\$191	\$50,384,828	\$280
2008	277,200	138,600	\$24,326,090	\$88	\$26,058,738	\$188	\$50,384,828	\$276
2009	281,600	140,800	\$24,326,090	\$86	\$26,058,738	\$185	\$50,384,828	\$271
2010	286,000	286,000	\$24,326,090	\$85	\$52,274,054	\$183	\$76,600,144	\$268
2011	290,400	290,400	\$24,326,090	\$84	\$52,274,054	\$180	\$76,600,144	\$264
2012	294,800	294,800	\$0	\$0	\$26,215,316	\$178	\$26,215,316	\$178
2013	299,200	299,200	\$0	\$0	\$26,215,316	\$175	\$26,215,316	\$175
2014	303,600	303,600	\$0	\$0	\$26,215,316	\$173	\$26,215,316	\$173
2015	308,000	308,000	\$0	\$0	\$0	\$0	\$0	\$0

5. Operating Costs

Operating costs include the cost for vehicle and engine maintenance, and the cost for vehicle consumables such as fuel, oil, filters and tires. The new standards and technologies introduced beginning in 2007 are expected to change vehicle operating costs. Costs for the refining and distribution of diesel fuel are expected to change due to the 15 ppm sulfur requirement. These costs are examined in detail later in this chapter (section V.D), but are also summarized here on a per vehicle basis. The closed crankcase systems we have described here include a paper filter element which is changed on a fixed service interval. The cost of this filter is included here as an ongoing operating cost. In addition the reduction of the sulfur content in diesel fuel is expected to lead to reduced maintenance costs or other cost savings in the design of future diesel engines. These cost savings are discussed in detail for both new and existing engines in section V.C and are summarized here on a per vehicle basis. The advanced emission control technologies expected to be applied in order to meet the NOx and PM/HC standards involve wholly new system components integrated into engine designs and calibrations, and as such may be expected to change the fuel consumption characteristics of the overall engine design. A discussion of the potential impacts of these technologies on vehicle fuel economy, and an explanation of why we do not expect vehicle fuel economy levels to change from today's levels are given here. All of these operating cost impacts are described here and are used to present a total per vehicle cost for control in tables V.A-2 and V.A-19.

a. Low Sulfur Diesel Fuel

Low sulfur diesel fuel is a primary enabling technology without which the other previously mentioned emission control technologies could not be applied. As an essential part of the technology package which enables the standards its cost are summarized here and in table V.A-2 on a per-vehicle cost basis (NPV).

The low-sulfur diesel fuel required to enable these technologies is expected to have a long term incremental cost of approximately \$0.05/gallon as discussed in more detail later in this chapter. This per gallon cost can be accounted for on a per vehicle basis by considering the mileage typically driven by a class of vehicle at each year of its life and the average fuel economy. Using that approach and bringing the total cost back to a net present value in the year of sale gives a long term per vehicle low sulfur fuel cost of \$609 for a light heavy-duty vehicle, \$1,141 for a medium heavy-duty vehicle, \$4,209 for a heavy heavy-duty vehicle and \$4,959 for an urban bus. For a more detailed discussion of the cost associated with low sulfur diesel fuel please refer to section V.D in this RIA.

b. Maintenance Costs for Closed Crankcase Ventilation Systems (CCV)

We have eliminated the exception that allows turbo-charged heavy-duty diesel engines to vent crankcase gases directly to the environment without accounting for these emissions, sometimes called open crankcase systems, and are projecting that manufacturers will rely on engineered closed crankcase ventilation systems which filter oil from the blow-by gases in order to satisfy the emission standard. An integral part of the system described in Chapter III of this RIA is a paper filter designed to capture oil mist in the blow-by gases, coalesce this oil and return this filtered oil to the oil sump. These filters are expected to require replacement on a fixed interval of 30,000 miles.

The cost of these filters in 2007 has been estimated to be \$10, \$12, and \$15 for light, medium, and heavy heavy-duty vehicles respectively. The variable cost for these replacement filters are reduced in future years due to the learning curve effect as described in section 6 below. The long term total life cycle operating cost for the filter replacements expressed as a net present value in the year of sale is \$26, \$48, and \$172 for light, medium, and heavy heavy-duty vehicles, respectively. Urban bus life cycle operating costs are estimated to be \$92. To account for the aggregate cost of filter replacement the filter costs are estimated on a per mile basis for each class of vehicle (for example for heavy heavy-duty this is \$15/30,000 miles) and then are estimated in total using typical mileage accumulation rates given in each year of a vehicles life from our inventory emissions model. The results of this calculation along with the maintenance costs for CDPFs are reported in table V.A-21.

c. Maintenance Costs for Catalyzed Diesel Particulate Filters

The particulate matter (PM) emitted from diesel engines consists primarily of elemental carbon formed during the combustion process from diesel fuel. This elemental carbon is captured in the CDPF and then oxidized to CO₂ and emitted from the engine. A very small fraction of the PM consists of inorganic metals which are also captured by the CDPF but are not emitted later from the CDPF. Instead this inorganic “ash” accumulates in the PM filter over time slowing filling the filtering passages of the CDPF. Current engine oil formulations are the primary source of this inorganic ash due to metal additives used in the oil.

The inorganic ash captured in the CDPF can be cleaned from the CDPF by removing it from the vehicle and reverse flushing the ash out of the CDPF with compressed air or water. Current industry guidelines suggest a maintenance interval for retrofit applications of approximately 60,000 miles for CDPF cleaning. This guideline reflects a fairly short maintenance interval because

- PM rates in retrofit applications are high (many retrofits are EURO 0, I, & II engines)¹⁵
- Oil consumption rates on older retrofit engines can be very high
- Current engine oils are highly additized to maintain Total Base Number (TBN).

We have estimated that for CDPF equipped vehicles in 2007 and beyond that the maintenance interval will increase to 100,000 miles for light heavy-duty vehicles and 150,000 miles for medium and heavy heavy-duty vehicles. We expect that this interval will be planned to coincide with other engine maintenance events and can be extended to these higher intervals because

- PM rates are lower for modern diesel engines
- Modern diesel engines have low oil consumption rates (to meet the PM standard)
- Low sulfur diesel fuel will allow the use of “low ash” engine oils.

We have estimated the cost of this service based upon the assumption that the service is scheduled to coincide with other service intervals and that the dominant cost for the service is the cost labor cost to remove and clean the filter. We have assumed that this removal and reinstallation will take approximately one hour. We have used a labor rate for this service event of \$65 / hour. These costs are aggregated on a fleet wide basis in each year of the program and reported in table V.A-21 along with the maintenance costs for the closed crankcase ventilation (CCV) system. The CDPF maintenance costs can also be expressed as a net present value in the year of sale for an individual vehicle as \$55 for a light heavy-duty vehicle, \$56 for a medium heavy-duty vehicle, \$208 for a heavy heavy-duty vehicle and \$107 for an urban bus.

d. Maintenance Savings due to Low Sulfur Diesel Fuel

In addition to its role as a technology enabler, low sulfur diesel fuel gives benefits in the form of reduced sulfur induced corrosion and slower acidification of engine lubricating oil, leading to longer maintenance intervals and lower maintenance costs. These benefits are described in detail in section V.C and result in an estimated savings of \$153 for light heavy-duty vehicles, \$249 for medium heavy-duty vehicles, and \$610 for heavy heavy-duty vehicles and urban buses.

e. Fuel Economy Impacts

Diesel particulate filters are anticipated to provide a step-wise decrease in diesel particulate (PM) emissions by trapping PM and by oxidizing the diesel PM and hydrocarbon (HC) emissions. The trapping of the very fine diesel PM is accomplished by forcing the exhaust through a porous filtering media with extremely small opening and long path lengths.^b This approach results in filtering efficiencies for diesel PM greater than 90 percent but requires additional pumping work to force the exhaust through these small openings. The additional pumping work is anticipated to negatively impact fuel economy by approximately one percent.¹⁶ However as detailed in the following discussion this fuel economy penalty is more than offset through optimization of the engine-PM trap-NOx adsorber system, as discussed below.

NOx adsorbers are expected to be the primary NOx control technology introduced in order to provide the reduction in NOx emissions necessary to meet the NOx standard. NOx adsorbers work by storing NOx emissions under fuel lean operating conditions (normal diesel engine operating conditions) and then by releasing and reducing the stored NOx emissions over a brief period of fuel rich engine operation. This brief periodic NOx release and reduction step is directly analogous to the catalytic reduction of NOx over a gasoline three-way-catalyst. In order for this catalyst function to occur the engine exhaust constituents and conditions must be similar to normal gasoline exhaust constituents. That is, the exhaust must be fuel rich (devoid of excess oxygen) and hot (over 250°C). Although it is anticipated that diesel engines can be made to operate in this way, it is assumed that the fuel economy of the diesel engine operating under these conditions will be worse than normal. This increase in fuel consumption can be minimized by carefully controlling engine air-to-fuel (A/F) ratios using the EGR systems introduced in order to meet the 2004 heavy duty engine emission standards. The lower the engine A/F ratio, the lower the amount of fuel which must be added in order to give rich conditions. In the ideal case where the engine A/F ratio is at stoichiometry, and additional fuel is required only as a NOx reductant the fuel economy penalty is virtually zero. We are projecting, that practical limitations on engine A/F control will mean that the NOx adsorber release and reduction cycles will lead to a one

^b Typically the filtering media is a porous ceramic monolith or a metallic fiber mesh.

percent decrease in the engine fuel economy. Again, we believe this fuel economy impact can be regained through optimization of the engine-PM trap-NOx adsorber system.

In addition to the NOx release and regeneration event, another step in NOx adsorber operation may affect fuel economy. NOx adsorbers are poisoned by sulfur in the fuel even at the low sulfur levels we have set today. Chapter III of this RIA describes how the sulfur poisoning of the NOx adsorber can be reversed through a periodic “desulfation” event. The desulfation of the NOx adsorber is accomplished in a manner similar to the NOx release and regeneration cycle described above. However it is anticipated that the desulfation event will require extended operation of the diesel engine at rich conditions.¹⁷ This rich operation will, like the NOx regeneration event, will lead to an increase in the fuel consumption rate and will cause an associated decrease in fuel economy. With a 15 ppm fuel sulfur cap, we are projecting this fuel economy penalty to be one percent or less as described in more detail in chapter III of this RIA. Again, we believe this fuel economy impact can be regained through optimization of the engine-PM trap-NOx adsorber system.

While NOx adsorbers require non-power producing consumption of diesel fuel in order to function properly and, therefore, have an impact on fuel economy, they are not unique among NOx control technologies in this way. In fact NOx adsorbers are likely to have a very favorable NOx to fuel economy trade-off when compared to other popular NOx control technologies like cooled EGR and injection timing retard. EGR requires the delivery of exhaust gas from the exhaust manifold to the intake manifold of the engine and causes a decrease in fuel economy for two reasons. The first of these reasons is that a certain amount of work is required to pump the EGR from the exhaust manifold to the intake manifold; this necessitates the use of intake throttling or some other means to accomplish this pumping. The second of these reasons is that heat in the exhaust, which is normally partially recovered as work across the turbine of the turbocharger, is instead lost to the engine coolant through the cooled EGR heat exchanger. In the end, cooled EGR is only some 50 percent effective at reducing NOx below the current 4 g/bhp-hr NOx emission standard. Injection timing retard is another strategy that can be employed to control NOx emissions. By retarding the introduction of fuel into the engine, and thus delaying the start of combustion, both the peak temperature and pressure of the combustion event are decreased; this lowers NOx formation rates and, ultimately, NOx emissions. Unfortunately, this also significantly decreases the thermal efficiency of the engine (lowers fuel economy) while also increasing PM emissions. As an example, retarding injection timing eight degrees can decrease NOx emissions by 45 percent, but this occurs at a fuel economy penalty of more than seven percent.¹⁸

Today, most diesel engines rely on injection timing control (retarding injection timing) in order to meet the 4.0 g/bhp-hr NOx emission standard. For 2002/2004 model year compliance, we expect that engine manufacturers will use a combination of cooled EGR and injection timing control to meet the 2.0 g/bhp-hr NOx standard. Because of the more favorable fuel economy

trade-off for NOx control with EGR when compared to timing control, we have forecast that less reliance on timing control will be needed in 2002/2004. Therefore, fuel economy will not be changed even at this lower NOx level. NOx adsorbers have a significantly more favorable NOx to fuel economy trade-off when compared to cooled EGR or timing retard.¹⁹ We expect NOx adsorbers to be able to accomplish a greater than 90 percent reduction in NOx emissions, while themselves consuming significantly less fuel than that lost through alternative NOx control strategies such as retarded injection timing.^c Therefore, we expect manufacturers to take full advantage of the NOx control capabilities of the NOx adsorber and project that they will decrease reliance on the more expensive (from a fuel economy standpoint) technologies, especially injection timing retard. We would, therefore, predict that the fuel economy impact currently associated with NOx control from timing retard will be decreased by at least three percent. In other words, through the application of these advanced NOx emission control technologies, we expect the NOx trade-off with fuel economy to continue to improve significantly when compared to today's technologies. This will result in much lower NOx emissions and potentially overall improvements in fuel economy, improvements that could easily offset the one percent fuel economy loss projected to result from the application of PM filters. For our analysis of economic impacts, no penalty or benefit for changes to fuel economy is assumed.

In order to illustrate the sensitivity of cost to fuel economy, we have calculated the benefit (or cost) of a one percent change in vehicle fuel economy as a sensitivity analysis to these possible changes. For a light heavy-duty engine a one percent change in vehicle fuel economy expressed as a net present value in the year of sale is approximately \$100, for a medium heavy-duty engine it is approximately \$200, for a heavy heavy-duty engine it is approximately \$800. The amount of the benefit (or cost) of a one percent change in fuel economy expressed in terms of its annual impact on the entire fleet of engines meeting the 2007 NOx standards can be estimated as \$155 million in 2010 and \$459 million in 2030. These potential benefits (or costs) represent approximately 4 percent of the total program cost in 2010 and less than 11 percent in 2030.

6. Summary of Near and Long Term Costs

We have estimated in section V.A.3 the cost of a technology package which is representative of the technologies we expect industry to apply to meet our standards. These cost estimates represent an expected incremental cost of engines in the 2007 model year. EPA has also identified various factors that would cause cost impacts to decrease over time, making it

^c EPA has estimated the fuel consumption rate for NOx regeneration and desulfation of the NOx adsorber as approximately 2 percent of total engine fuel consumption. This differs from the contractor report by EF&EE which estimates the total consumption as approximately 2.5% of total fuel consumption. Additionally the contractor's estimate of NOx adsorber efficiency ranges from 80-90 percent, while EPA believes over 90 percent control is possible as discussed fully in Chapter III of this RIA.

appropriate to distinguish between near-term and long term costs. These factors are described below and the resulting near and long term per vehicle costs are presented here.

First, initial fixed costs for tooling, R&D, and certification are recovered over a five-year period phased with the NO_x standard phase-in period. Fixed costs are therefore accrued in four periods corresponding to each of the phase-in years of the NO_x standard. The accrued costs are then recovered over a five year period.

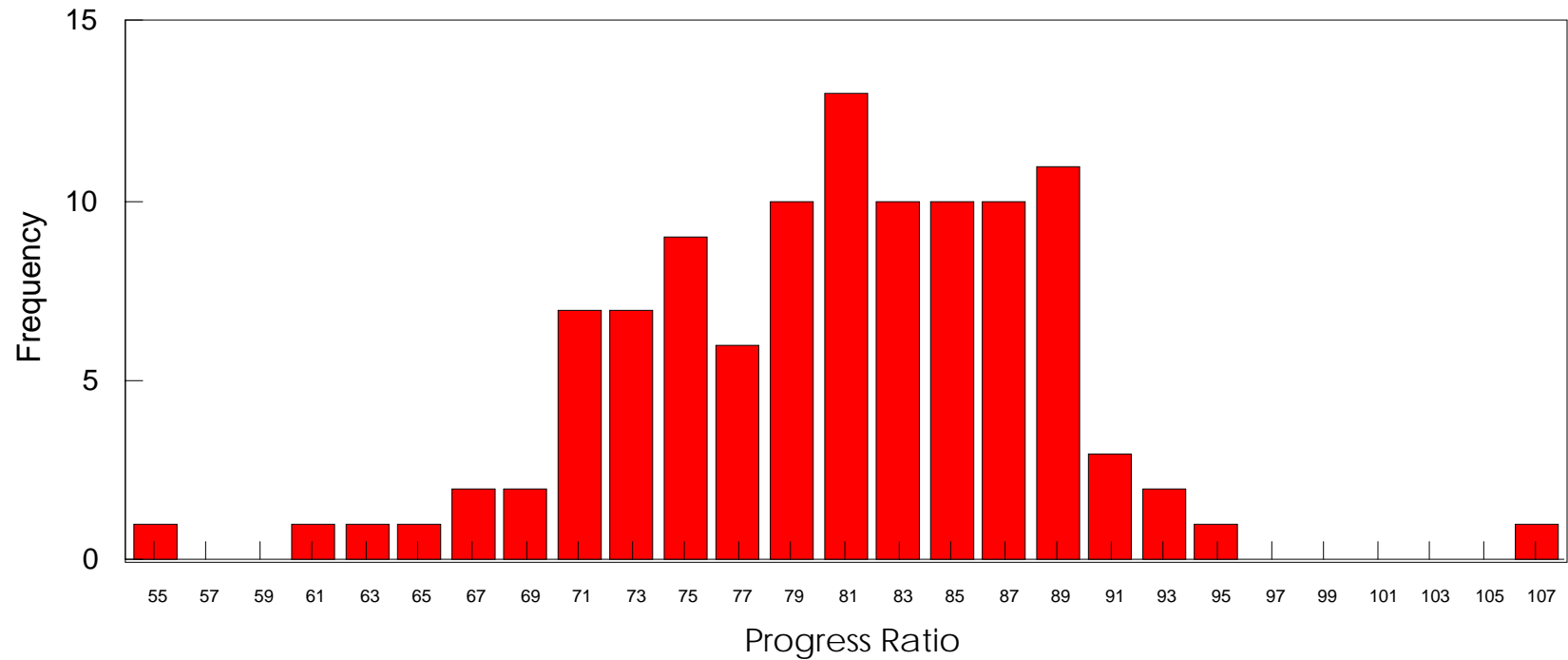
For variable costs, research in the costs of manufacturing has shown that as manufacturers gain experience in production, they are able to lower the per-unit cost of production. These effects are often described as the manufacturing learning curve.²⁰

The learning curve is a well documented phenomenon dating back to the 1930s. The general concept is that unit costs decrease as cumulative production increases. Learning curves are often characterized in terms of a progress ratio, where each doubling of cumulative production leads to a reduction in unit cost to a percentage "p" of its former value (referred to as a "p cycle"). The organizational learning which brings about a reduction in total cost is caused by improvements in several areas. Areas involving direct labor and material are usually the source of the greatest savings. Examples include, but are not limited to, a reduction in the number or complexity of component parts, improved component production, improved assembly speed and processes, reduced error rates, and improved manufacturing process. These all result in higher overall production, less scrappage of materials and products, and better overall quality. As each successive p cycle takes longer to complete, production proficiency generally reaches a relatively stable plateau, beyond which increased production does not necessarily lead to markedly decreased costs.

Companies and industry sectors learn differently. In a 1984 publication, Dutton and Thomas reviewed the progress ratios for 108 manufactured items from 22 separate field studies representing a variety of products and services.²¹ The distribution of these progress ratios is shown in Figure V-1. Except for one company that saw *increasing* costs as production continued, every study showed cost savings of at least five percent for every doubling of production volume. The average progress ratio for the whole data set falls between 81 and 82 percent. Other studies (Alchian 1963, Argote and Epple 1990, Benkard 1999) appear to support the commonly used p value of 80 percent, i.e., each doubling of cumulative production reduces the former cost level by 20 percent.

The learning curve is not the same in all industries. For example, the effect of the learning curve seems to be less in the chemical industry and the nuclear power industry where a

Distribution of Progress Ratios



From 22 field studies (n = 108).

Figure V.A-1. Distribution of Progress Ratios
(Dutton and Thomas, 1984)

doubling of cumulative output is associated with 11% decrease in cost (Lieberman 1984, Zimmerman 1982). The effect of learning is more difficult to decipher in the computer chip industry (Gruber 1992).

EPA believes the use of the learning curve is appropriate to consider in assessing the cost impact of heavy-duty engine emission controls. The learning curve applies to new technology, new manufacturing operations, new parts, and new assembly operations. Heavy-duty diesel engines currently do not use any form of NO_x aftertreatment and have used diesel particulate filters in only limited application. These are therefore new technologies for heavy-duty diesel engines and will involve new manufacturing operations, new parts, and new assembly operations. Since this will be a new and unique product, EPA believes this is an appropriate situation for the learning curve concept to apply. Opportunities to reduce unit labor and material costs and increase productivity (as discussed above) will be great. EPA believes a similar opportunity exists for the new control systems which will integrate the function of the engine and the emission control technologies. While all diesel engines beginning in 2004 are expected to have the basic components of this system, advanced engine control modules (computers), advanced engine air management systems (cooled EGR, and variable geometry turbocharging) and advanced fuel systems including common rail systems, they will now be applied in new ways. Additionally some new components will be applied for the first time. These new parts and new assemblies will involve new manufacturing operations. As manufacturers gain experience with these new systems, comparable learning is expected to occur with respect to unit labor and material costs. These changes require manufacturers to start new production procedures, which, over time, will improve with experience.

We have applied a p value of 80 percent beginning in 2007 in this analysis. That is, variable costs were reduced by 20 percent for each doubling of cumulative production. With one year as the base unit of production, the first learning curve is applied at the start of 2009. The second doubling of production occurs at the end of the 2010 model year, therefore variable costs are reduced a second time by 20 percent beginning in the 2011 model year. In Tier 2, and in the heavy-duty gasoline cost analysis presented in section B of this chapter, the learning curve reduction was applied only once because we anticipated that for the most part the standards will be met through improvements to existing technologies rather than through the use of new technologies. With existing technologies, there will be less opportunity for lowering production costs.

Fixed costs for this program have been allocated for two separate groups of vehicle representing vehicles introduced in the first and fourth years of NO_x phase in period. In this way fixed costs on a per vehicle basis are appropriately weighted for the number of vehicles introduced in that model year. The manufacturers are expected to accrue fixed cost in proportion to the number of vehicles being introduced in a model year as we have done here. This means that fixed costs are assumed to begin accruing in 2002 for vehicles intended for introduction in

2007 and to continue to be accrued through 2009 for vehicles intended for introduction in 2010. Fixed costs are therefore assumed to be recovered beginning in 2007 (for vehicles introduced in 2007) and continuing through 2014 for vehicles introduced in 2010, the final year of the NOx phase-in. For all per vehicle costs, the fixed costs are reported for vehicles first introduced in 2007 and are therefore fully recovered by 2012. For a more complete description of fixed costs see section V.A.4 of this RIA.

The resulting hardware and life cycle operating costs for new vehicles developed to meet the new 2007 heavy-duty vehicle standards are summarized in table V.A-19 below.

**Table V.A-19. Projected Incremental Diesel Engine/Vehicle Costs
(net present value at point of sale in 1999 dollars)**

<i>Vehicle Class</i>	<i>Model Year</i>	<i>Change</i>	<i>Hardware Cost</i>	<i>Life-cycle Operating Cost (NPV)</i>
Light heavy-duty	2007	—	\$1,986	\$509
	2009	20 percent learning curve applied to variable costs	\$1,601	\$509
	2012	Fixed costs expire; 20 percent learning curve has been applied to variable costs	\$1,173	\$537
Medium heavy-duty	2007	—	\$2,564	\$943
	2009	20 percent learning curve applied to variable costs	\$2,096	\$943
	2012	Fixed costs expire; 20 percent learning curve has been applied to variable costs	\$1,412	\$996
Heavy heavy-duty	2007	—	\$3,227	\$3,785
	2009	20 percent learning curve applied to variable costs	\$2,618	\$3,785
	2012	Fixed costs expire; 20 percent learning curve has been applied to variable costs	\$1,866	\$3,979
Urban Bus	2007	—	\$2,889	\$4,625
	2009	20 percent learning curve applied to variable costs	\$2,347	\$4,625
	2012	Fixed costs expire; 20 percent learning curve has been applied to variable costs	\$1,650	\$4,797

It is appropriate to compare the impact of these incremental costs to the total cost to purchase and operate these vehicles. The analysis for the 2004 heavy duty engine standards included work to document the cost to purchase and operate heavy duty vehicles. That analysis is carried forward here and is given in Table V.A-20 after being adjusted to 1999 dollars. From the table we can see that in the near term and long term vehicle operating costs can be expected to increase by less four percent for all vehicle weight classes. Near term vehicle costs on average will be expected to increase by approximately five percent. In the long term vehicle costs will be increased by less than five percent for light heavy-duty vehicles, by less than three percent for medium heavy-duty vehicles, and by less than two percent heavy heavy-duty vehicles and urban buses.

Table V.A-20. Baseline Costs for Heavy-Duty Engines and Vehicles ²²

<i>Vehicle Class</i>	<i>Engine Cost</i>	<i>Vehicle Cost</i>	<i>Operating Costs</i>
Light heavy-duty	\$8,527	\$24,600	\$13,610
Medium heavy-duty	\$13,555	\$50,430	\$34,153
Heavy heavy-duty	\$23,722	\$105,481	\$118,093
Urban Bus	\$24,050	\$244,871	\$477,885

7. Total Incremental Nationwide Costs for 2007 Heavy-Duty Diesel Engines

The above analysis develops per-vehicle cost estimates for each vehicle class. With current data for the size and characteristics of the heavy-duty vehicle fleet and projections for the future, these costs can be translated into a total cost to the nation for the emission standards in any year. The result of this analysis are presented in the following tables which summarize the total incremental cost for new vehicles introduced into the fleet for each model year.

Fixed costs have been previously developed for each class of heavy duty vehicle and are presented in section V.A.4 of this RIA. Those costs have been totaled here to present the total annualized and non-annualized fixed costs for the engine control under this program. Variable costs are computed as a product of one full year of heavy-duty vehicle sales and the cost increase for the new hardware on a per vehicle basis as developed previously. The operating cost for the closed crankcase filtration systems and for cleaning CDPF catalysts are included here as well. The operating cost associated with low sulfur diesel fuel and the savings associated with low sulfur diesel fuel are summarized on an aggregate basis later in this chapter.

The total annualized cost for the hardware changes are given in table V.A-21 below. Non-annualized costs are also given below in table V.A-22.

**Table V.A-21. Estimated Annualized Nationwide Costs for Heavy-Duty Diesel Engines
Associated with the 2007 Emission Standard**
(1999 dollars)

<i>Calendar Year</i>	<i>Projected Vehicle Sales</i>	<i>Fixed Costs</i>	<i>Variable Costs</i>	<i>CCV and CDPF Maintenance Costs</i>	<i>Total Costs</i>
2007	787,400	\$116,345,286	\$1,373,511,459	\$22,066,902	\$1,511,923,648
2008	800,200	\$116,345,286	\$1,395,802,627	\$58,732,341	\$1,570,880,255
2009	813,000	\$116,345,286	\$1,126,415,636	\$82,987,152	\$1,325,748,074
2010	825,800	\$177,574,633	\$1,521,698,170	\$110,217,085	\$1,809,489,888
2011	838,600	\$177,574,633	\$1,227,885,771	\$123,307,106	\$1,528,767,511
2012	851,400	\$61,229,347	\$1,246,599,207	\$143,989,773	\$1,451,818,326
2013	864,200	\$61,229,347	\$1,265,312,642	\$162,942,107	\$1,489,484,096
2014	877,000	\$61,229,347	\$1,284,026,077	\$180,369,083	\$1,525,624,507
2015	889,800	\$0	\$1,302,739,513	\$196,453,205	\$1,499,192,718
2016	902,600	\$0	\$1,321,452,948	\$211,356,424	\$1,532,809,372
2017	915,400	\$0	\$1,340,166,383	\$225,221,746	\$1,565,388,129
2018	928,200	\$0	\$1,358,879,819	\$238,175,421	\$1,597,055,240
2019	941,000	\$0	\$1,377,593,254	\$250,327,361	\$1,627,920,615
2020	953,800	\$0	\$1,396,306,689	\$261,771,775	\$1,658,078,464
2021	966,600	\$0	\$1,415,020,124	\$272,586,752	\$1,687,606,876
2022	979,400	\$0	\$1,433,733,560	\$282,835,130	\$1,716,568,690
2023	992,200	\$0	\$1,452,446,995	\$292,570,241	\$1,745,017,236
2024	1,005,000	\$0	\$1,471,160,430	\$301,857,197	\$1,773,017,627
2025	1,017,800	\$0	\$1,489,873,866	\$310,779,520	\$1,800,653,386
2026	1,030,600	\$0	\$1,508,587,301	\$319,383,848	\$1,827,971,149
2027	1,043,400	\$0	\$1,527,300,736	\$327,711,027	\$1,855,011,763
2028	1,056,200	\$0	\$1,546,014,172	\$335,796,605	\$1,881,810,777
2029	1,069,000	\$0	\$1,564,727,607	\$343,671,733	\$1,908,399,340
2030	1,081,800	\$0	\$1,583,441,042	\$351,363,512	\$1,934,804,554
2031	1,094,600	\$0	\$1,602,154,478	\$358,926,832	\$1,961,081,310
2032	1,107,400	\$0	\$1,620,867,913	\$366,345,968	\$1,987,213,881
2033	1,120,200	\$0	\$1,639,581,348	\$373,585,640	\$2,013,166,988
2034	1,133,000	\$0	\$1,658,294,784	\$380,771,649	\$2,039,066,433
2035	1,145,800	\$0	\$1,677,008,219	\$387,852,302	\$2,064,860,521

Table V.A-22. Estimated Non-Annualized Nationwide Costs for Heavy-Duty Diesel Engines Associated with the 2007 Emission Standard (1999 dollars)

<i>Calendar Year</i>	<i>Fixed Costs</i>	<i>Variable Costs</i>	<i>CCV and CDPF Maintenance Costs</i>	<i>Total Costs</i>
2002	\$78,961,850	\$0	\$0	\$78,961,850
2003	\$78,961,850	\$0	\$0	\$78,961,850
2004	\$78,961,850	\$0	\$0	\$78,961,850
2005	\$121,176,000	\$0	\$0	\$121,176,000
2006	\$142,624,275	\$0	\$0	\$142,624,275
2007	\$42,214,150	\$1,373,511,459	\$22,066,902	\$1,437,792,511
2008	\$42,214,150	\$1,395,802,627	\$58,732,341	\$1,496,749,118
2009	\$49,961,675	\$1,126,415,636	\$82,987,152	\$1,259,364,463
2010	\$0	\$1,521,698,170	\$110,217,085	\$1,631,915,255
2011	\$0	\$1,227,885,771	\$123,307,106	\$1,351,192,877
2012	\$0	\$1,246,599,207	\$143,989,773	\$1,390,588,980
2013	\$0	\$1,265,312,642	\$162,942,107	\$1,428,254,749
2014	\$0	\$1,284,026,077	\$180,369,083	\$1,464,395,160
2015	\$0	\$1,302,739,513	\$196,453,205	\$1,499,192,718
2016	\$0	\$1,321,452,948	\$211,356,424	\$1,532,809,372
2017	\$0	\$1,340,166,383	\$225,221,746	\$1,565,388,129
2018	\$0	\$1,358,879,819	\$238,175,421	\$1,597,055,240
2019	\$0	\$1,377,593,254	\$250,327,361	\$1,627,920,615
2020	\$0	\$1,396,306,689	\$261,771,775	\$1,658,078,464
2021	\$0	\$1,415,020,124	\$272,586,752	\$1,687,606,876
2022	\$0	\$1,433,733,560	\$282,835,130	\$1,716,568,690
2023	\$0	\$1,452,446,995	\$292,570,241	\$1,745,017,236
2024	\$0	\$1,471,160,430	\$301,857,197	\$1,773,017,627
2025	\$0	\$1,489,873,866	\$310,779,520	\$1,800,653,386
2026	\$0	\$1,508,587,301	\$319,383,848	\$1,827,971,149
2027	\$0	\$1,527,300,736	\$327,711,027	\$1,855,011,763
2028	\$0	\$1,546,014,172	\$335,796,605	\$1,881,810,777
2029	\$0	\$1,564,727,607	\$343,671,733	\$1,908,399,340
2030	\$0	\$1,583,441,042	\$351,363,512	\$1,934,804,554
2031	\$0	\$1,602,154,478	\$358,926,832	\$1,961,081,310
2032	\$0	\$1,620,867,913	\$366,345,968	\$1,987,213,881
2033	\$0	\$1,639,581,348	\$373,585,640	\$2,013,166,988
2034	\$0	\$1,658,294,784	\$380,771,649	\$2,039,066,433
2035	\$0	\$1,677,008,219	\$387,852,302	\$2,064,860,521

B. Economic Impact of the 2008 Model Year Heavy-Duty Gasoline Standards

This chapter contains an analysis of the economic impacts of the emission standards for 2008 model year heavy-duty gasoline vehicles and engines. First, a brief outline of the methodology used to estimate the economic impacts is presented, followed by a summary of the technology packages that are expected to be used to meet the standards. Next, the projected costs of the individual technologies is presented, along with a discussion of fixed costs such as research and development (R&D), tooling and certification costs. Following the discussion of the individual cost components is a summary of the projected per-vehicle cost. Finally, an analysis of the aggregate cost to society of the new standards is presented. The costs presented here are in 1999 dollars.

1. Methodology for Estimating Heavy-Duty Gasoline Costs

This analysis uses the emission control technology packages assumed for the final Phase 1 gasoline standards as a baseline from which changes will be made to comply with the new Phase 2 standards. The Phase 1 standards go into effect for the 2004 or 2005 model year.²³ That is, we have identified the changes we expect to be made to the assumed 2005 baseline vehicles in complying with the new 2008 standards. The 2005 baseline technology packages are consistent with those being implemented to meet California's Low Emission Vehicle (LEV I) standards. The technology packages assumed for the 2008 model year are consistent with those expected to meet the California LEV-II medium-duty vehicle standards and our light-duty Tier 2 standards.^{d,24} The catalyst system costs of these technologies are taken from the Phase 1 RIA, which are based on a report done for EPA by Arcadis Geraghty & Miller.²⁵ Other system costs are taken from the final Tier 2 RIA, which are based in part on California's LEV-II analysis and the same Arcadis Geraghty & Miller report.

The costs of meeting the 2008 emission standards include both variable costs (incremental hardware costs, assembly costs, and associated markups) and fixed costs (tooling, R&D, and certification costs). Supplier markups, those markups occurring between the part or emission control system supplier to the vehicle or engine manufacturer, are applied to catalyst costs in this analysis because the cost we estimated for each element comprising the catalyst are the supplier cost rather than the vehicle or engine manufacturer cost. This contrasts with the diesel cost analysis discussed in Section V.A where the cost of each element comprising a PM trap or a NOx adsorber are costs to the vehicle manufacturer (i.e., they already contain a supplier

^d While the Tier 2 standards are light-duty standards, and do not apply to the vehicles and engines covered by this analysis, we expect that the technologies employed to meet the Tier 2 standards will transfer in large part into the heavy-duty gasoline fleet; therefore, the types of technology packages are expected to be very similar.

markup). An exception to applying the supplier markup has been made for precious metals. Vehicle manufacturers typically provide catalyst suppliers with precious metals for use in the catalysts their suppliers manufacture. Thus, the 29 percent supplier markup is not applied to the cost of precious metals. The supplier markup is already reflected in the non-catalyst system costs (e.g., EGR system, secondary air injection system, etc.) presented in this section.

The variable costs to the manufacturer have then been marked up twice.²⁶ The first markup, at a four percent rate, covers manufacturer carrying costs reflecting primarily the costs of capital tied up in extra inventory, and secondarily the incremental cost of insurance, handling, and storage. The second markup, at a three percent rate, covers dealer carrying costs reflecting the cost of capital tied up in extra inventory. These markups were discussed in more detail in section A of this chapter. Fixed costs were amortized at a seven percent rate and recovered over a five year period.

2. Technology Packages for Compliance with the 2008 Model Year Heavy-Duty Gasoline Standards

The various technologies that could be used to comply with the proposed regulations were discussed in Chapter 3. We expect that the technology mixes used to meet the California LEV-II standards, and our Tier 2 standards, fairly accurately represent those that will be used to comply with the 2008 heavy-duty gasoline standards. Thus, in developing costs for the technology packages we expect to be used, we started with the technology packages assumed to be implemented on HD gasoline vehicles and engines to meet the 2005 standards. Table 5.B-1 shows both the expected 2005 technology packages, the baseline for this analysis, and the expected 2008 technology packages for both complete and incomplete gasoline vehicles. The expected technologies for 2008 are consistent between vehicles and engines; we make this assumption based on our belief that the standards for vehicles and engines are equivalently stringent.

This table only shows the technologies which are expected to change in some way or to be applied in different percentages to meet the 2008 standards. A technology like sequential multi-port fuel injection, while important to meeting the new standards, is expected on 100 percent of the 2005 vehicles and engines, and its design is not expected to fundamentally change for 2008. As a result, we expect no incremental changes or costs associated with that technology, and it is not included in the table. However, the table does contain technologies we believe will be more widely implemented, but which have no associated costs for their implementation. One such example, spark retard on engine start up, is expected to be more widely implemented for the 2008 standards, but there are no costs associated with implementing that technology. Such technologies are included in these tables for completeness, but do not appear in later tables showing the incremental costs associated with the 2008 standards.

Table V.B-1. 2005 (Phase 1) and Expected 2008 (Phase 2) Technology Packages for Heavy-Duty Gasoline Vehicles excluding Medium-Duty Passenger Vehicles

<i>Technology</i>	<i>2005 Complete Vehicles</i>	<i>2005 Incomplete Vehicles (Engine-Based)</i>	<i>2008 Expected for Complete and Incomplete Vehicles</i>
Catalysts ^A	13% single underfloor 50% dual underfloor 37% dual close-coupled with dual underfloor	13% single underfloor 87% dual underfloor	50% dual underfloor 50% dual close-coupled with dual underfloor
Oxygen sensors ^B	13% dual heated 87% four heated	13% triple heated 87% four heated	100% four heated with two being fast light-off
EGR	85% -- All electronic	85% -- All electronic	100% -- All electronic
Adaptive learning	80%	80%	100%
Heat managed exhaust ^C	40%	0%	80% ^D
Secondary air injection with closed-loop control	30%	50%	50%
Spark retard at start-up	0%	0%	100%

^A In addition to the change in catalyst configurations shown, we expect that catalyst washcoat and precious metal compositions and loadings will change.

^B The estimated breakdown for 2005 reflects OBD requirements for all HDGEs. However, OBD is only required on HDGEs under 14,000 lbs GVWR (approximately 60 percent of HDGEs).

^C May include air gaps, thin walls, low thermal capacity manifold, insulation, etc.

^D 100 percent of those having dual underfloor catalysts, and 60 percent of those having dual close-coupled w/ dual underfloor catalysts.

3. Technology/Hardware Costs for Gasoline Vehicles and Engines

The following sections present the costs of the technologies we expect will be used to comply with the 2008 standards. Because most heavy-duty gasoline manufacturers offer more than one engine for their heavy-duty gasoline product line, cost estimates have been developed for a standard engine size and a larger engine size.

a. Improved Catalysts and Catalyst Systems

Improvements in catalyst systems fall into two broad categories: changes in catalyst system configuration and changes in the catalyst precious metal and washcoat compositions and loadings. In addition to estimating costs for these improvements, we have estimated the increased costs of substrates and packaging (cans) for the improved catalysts.

i. *Changes in Catalyst Configurations*

For heavy-duty gasoline vehicles and engines, we expect there to be generally three catalyst configurations for meeting the 2005 and 2008 standards -- the single underfloor, the dual underfloor, and the dual close-coupled combined with the dual underfloor. With the single underfloor catalyst system, the exhaust streams from both banks of engine cylinders “Y” into a single catalyst. With the dual underfloor catalyst system, each bank of engine cylinders exhausts into its own catalyst. With a dual close-coupled catalyst system, each bank of engine cylinders exhausts directly into a small, often called “pipe,” catalyst, and then into a dual underfloor main catalyst system.

For 2005, we estimate that: 13 percent of vehicles will employ a single underfloor catalyst; 50 percent of vehicles will employ dual underfloor catalysts; and, 37 percent of vehicles will employ dual close-coupled with dual underfloor catalysts. For 2008, we expect that 50 percent of vehicles will employ dual underfloor with the remaining 50 percent employing dual close-coupled catalysts with a dual underfloor. For engine based systems in 2005, we estimate that: 13 percent of engines will employ a single underfloor catalyst; and, 87 percent will employ dual underfloor catalysts. For 2008, we expect that engines will employ the same configurations as outlined above for vehicles. We believe these vehicle and engine catalyst configuration estimates to be reasonable given the estimated catalyst configuration employment in our Tier 2 analysis for MDPVs (80 percent with dual close-coupled and either single or dual underfloor configurations), and some previously done Arcadis estimates for standards similar to our 2008 standards.²⁷

ii. Changes in Catalyst Volumes and Precious Metal Loadings

The catalyst configuration changes and associated costs discussed above do not include changes in the precious metal and washcoat compositions and loadings. Gasoline vehicle catalysts have typically used some combination of platinum (Pt), palladium (Pd) and rhodium (Rh). These precious metals, or platinum group metals (PGM), account for a significant portion of the catalyst cost. Historically, a Pt/Rh combination has been used, but Pd has been seeing increased use in recent years. Pd is more thermally stable than Pt and Rh, which makes it a good choice for close-coupled catalysts, which are typically 100 percent Pd, where much higher temperatures are experienced. For 2005, we estimate a Pt/Pd/Rh ratio of 0/10/1 applied at a PGM loading of 4 grams/liter (g/L) for vehicles and 4.5 g/L for engines. For 2008, we estimate that the ratio will change to 1/14/1, consistent with Tier 2, at a loading of 5 g/L.²⁸

We have also estimated that catalyst volumes will increase. For 2005, we assume catalyst volumes will be 4.8 liters for the standard engines and 5.8 liters for the larger engines. Because the 2008 standards are more stringent, we expect that catalyst volumes will need to increase to 5.2 liters and 6.4 liters, respectively. In our Tier 2 analysis, we assumed that catalyst volumes would increase to equal engine displacement volume; however, we assumed no increase in precious metal loading.^e While the catalyst volumes we are assuming for 2008 may be low for some applications and high for others (2000 model year certified engine displacements ranged from 4.2 L to 8.0 L), we believe that we have chosen the appropriate middle ground of likely catalyst volumes.

The estimated costs associated with increased use of precious metals are summarized in Table V.B-2.

^e We assume a higher precious metal loading than our recent Tier 2 analysis because heavy-duty vehicles, by definition, undergo more rigorous operation during normal use. Therefore, more precious metals would probably be required to maintain acceptable emissions durability characteristics.

Table V.B-2. Costs Associated with the Increased Use of Precious Metals

Vehicles																	
	Projected 2005 Catalyst Volume (L)	Projected 2008 Catalyst Volume (L)	2005 Catalyst Loading (g/L)	2008 Catslyst Loading (g/L)	2005 Pt/Pd/Rh	2008 Pt/Pd/Rh	2005 Pt (g)	2005 Pd (g)	2005 Rh (g)	2008 Pt (g)	2008 Pd (g)	2008 Rh (g)	Increased Pt (g)	Increased Pd (g)	Increased Rh (g)	2005 PGM Cost (\$)	2008 PGM Cost (\$)
Standard Engine	4.8	5.2	4	5	0/10/1	1/14/1	0.000	17.455	1.745	1.625	22.750	1.625	1.625	5.295	-0.120	267.60	352.17
Larger Engine	5.8	6.4	4	5	0/10/1	1/14/1	0.000	21.091	2.109	2.000	28.000	2.000	2.000	6.909	-0.109	323.35	433.44

Engines																	
	Projected 2005 Catalyst Volume (L)	Projected 2008 Catalyst Volume (L)	2005 Catalyst Loading (g/L)	2008 Catslyst Loading (g/L)	2005 Pt/Pd/Rh	2008 Pt/Pd/Rh	2005 Pt (g)	2005 Pd (g)	2005 Rh (g)	2008 Pt (g)	2008 Pd (g)	2008 Rh (g)	Increased Pt (g)	Increased Pd (g)	Increased Rh (g)	2005 PGM Cost (\$)	2008 PGM Cost (\$)
Standard Engine	4.8	5.2	4.5	5	0/10/1	1/14/1	0.000	19.636	1.964	1.625	22.750	1.625	1.625	3.114	-0.339	301.05	352.17
Larger Engine	5.8	6.4	4.5	5	0/10/1	1/14/1	0.000	23.727	2.373	2.000	28.000	2.000	2.000	4.273	-0.373	363.77	433.44

Precious Metal Costs (9/29/99)

	\$/Troy Oz	\$/gram
Platinum	412	13.25
Paladium	390	12.54
Rhodium	868	27.91

iii. Changes in Catalyst Washcoat

In addition to the changes to precious metals just discussed, we expect that the 2008 standards will also result in changes to the catalyst washcoat compositions and loadings. Current washcoats are typically a combination of a cerium oxide blend (ceria) and aluminum oxide (alumina). Current ratios of these two components range from 75 percent ceria/25 percent alumina to 100 percent alumina. Of the two common washcoat components, ceria is more thermally stable and, thus, is expected in higher concentrations in close-coupled catalysts. We assume that a 75/25 ratio of ceria to alumina will be used to comply with the 2005 vehicle-based standards and that an even higher 80/20 ratio of ceria to alumina will be used to comply with the engine-based standards. For 2008, we are assuming that all washcoats will use an 80/20 ratio of ceria to alumina.

Current washcoat loadings range from 160 to 220 g/L of catalyst substrate volume. For 2005, we assume an average loading of 190 g/L for vehicle-based systems, and 220 g/L for engine-based systems. For 2008, we are assuming a loading of 220 g/L for all substrates. In addition, we expect that a new technique of layering the washcoat and precious metals will be employed. Currently, the precious metals and washcoat are applied to the catalyst substrate in a single slurry. Under the layering approach, there is a separate slurry for each precious metal, with the second slurry being applied after the first dries. This process allows for more reaction surface area, resulting in a more efficient catalyst.

iv. Catalyst Substrates

The substrate that the precious metals and washcoat are affixed to are typically ceramic substrates of 400 cells per inch. Increasing efforts are going into developing metallic substrates, which offer better temperature and vibration stability, as well as requiring less precious metal loading to achieve the same emission benefits. Since the increased costs of the metal substrates will tend to cancel out any savings in precious metal costs, we assumed that the current ceramic substrate would continue to be used to comply with the 2005 standards. We are assuming the same for the 2008 standards. The following linear relationship has been shown to be accurate for ceramic substrates sized from 0.5 L to 4 L:²⁹

$$C = \$4.67V + \$1.50$$

where:

C = cost to the vehicle manufacturer from the substrate supplier

V = substrate volume in liters

We are including an increased substrate cost due to the larger expected catalyst volumes; larger catalysts will need larger substrates. Generally, catalyst substrates for heavy-duty gasoline

vehicles and engines are manufactured in bricks no larger than 2.5 L, with a catalyst of greater than 2.5 L being comprised of more than one brick.

v. *Catalyst Packaging*

The final cost component of the catalyst system is the catalyst can. The catalyst substrate is typically packaged in a can made of 409 stainless steel and around 0.12 centimeters thick (18 gauge). The increased catalyst volumes expected for 2008 model year catalysts will result in more stainless steel and, therefore, more cost. The cost of the can is a very small portion of the overall catalyst cost.

vi. *Summary of Catalyst Costs*

Table V.B-3 shows our estimates of the total catalyst system cost for each of the three configurations previously discussed for the 2005 and 2008 standards. This table includes catalyst costs for standard size and larger size engines for applications certified to the vehicle or the engine standards. The Pt/Pd/Rh costs are taken from Table V.B-2 and do not have a supplier markup applied because we have been informed that the vehicle manufacturer purchases the precious metals and provides them to their catalyst supplier. Included in the table are incremental costs for ease of comparison. No costs are shown for a single underfloor catalyst system for 2008 because we do not expect any such applications in 2008.

Table V.B-3. Costs Associated with Various Catalyst Configurations

Single Underfloor Catalyst System

	Complete Vehicles				Incomplete Vehicles			
	2005 Vehicle		2008 Vehicle		2005 Engine		2008 Engine	
	Standard	Larger	Standard	Larger	Standard	Larger	Standard	Larger
Catalyst Volume (liters)	4.8	5.8	n/a	n/a	4.8	5.8	n/a	n/a
Substrate*	\$25	\$31			\$25	\$31		
Washcoat**	\$18	\$22			\$22	\$26		
Pt/Pd/Rh	\$268	\$323			\$301	\$364		
Can (18 gauge 409 SS)**	\$5	\$5			\$5	\$5		
Total Material Cost	\$321	\$387			\$358	\$431		
Labor	\$4	\$4			\$6	\$6		
Labor Overhead @ 40%	\$2	\$2			\$2	\$2		
Supplier Markup @ 29% ***	\$8	\$9			\$10	\$11		
Manufacturer Cost	\$335	\$402			\$377	\$451		
Manufacturer Carrying Cost @ 4%	\$13	\$16			\$15	\$18		
Total Cost to Dealer	\$348	\$418			\$392	\$469		
Incremental Cost			n/a	n/a			n/a	n/a

Dual Underfloor Catalyst System

	Complete Vehicles				Incomplete Vehicles			
	2005 Vehicle		2008 Vehicle		2005 Engine		2008 Engine	
	Standard	Larger	Standard	Larger	Standard	Larger	Standard	Larger
Catalyst Volume (liters)	4.8	5.8	5.2	6.4	4.8	5.8	5.2	6.4
Substrate*	\$25	\$31	\$27	\$34	\$25	\$31	\$27	\$34
Washcoat**	\$18	\$22	\$24	\$29	\$22	\$26	\$24	\$29
Pt/Pd/Rh	\$268	\$323	\$352	\$433	\$301	\$364	\$352	\$433
Can (18 gauge 409 SS)**	\$5	\$6	\$6	\$7	\$5	\$6	\$6	\$7
Total Material Cost	\$321	\$388	\$415	\$510	\$358	\$432	\$415	\$510
Labor	\$7	\$8	\$11	\$13	\$11	\$12	\$11	\$13
Labor Overhead @ 40%	\$3	\$3	\$4	\$5	\$4	\$5	\$4	\$5
Supplier Markup @ 29% ***	\$10	\$11	\$13	\$16	\$12	\$14	\$13	\$16
Manufacturer Cost	\$340	\$410	\$443	\$543	\$386	\$463	\$443	\$543
Manufacturer Carrying Cost @ 4%	\$14	\$16	\$18	\$22	\$15	\$19	\$18	\$22
Total Cost to Dealer	\$354	\$427	\$461	\$565	\$401	\$482	\$461	\$565
Incremental Cost			\$107	\$139			\$60	\$84

Dual Close-coupled with Dual Underfloor Catalyst System

	Complete Vehicles				Incomplete Vehicles			
	2005 Vehicle		2008 Vehicle		2005 Engine		2008 Engine	
	Standard	Larger	Standard	Larger	Standard	Larger	Standard	Larger
Catalyst Volume (liters)	4.8	5.8	5.2	6.4	4.8	5.8	5.2	6.4
Substrate****	\$28	\$33	\$30	\$36	\$28	\$33	\$30	\$36
Washcoat**	\$19	\$23	\$24	\$29	\$19	\$23	\$24	\$29
Pt/Pd/Rh	\$268	\$323	\$352	\$433	\$301	\$364	\$352	\$433
Can (18 gauge 409 SS)**	\$6	\$7	\$7	\$8	\$7	\$8	\$7	\$8
Total Material Cost	\$325	\$392	\$418	\$513	\$360	\$434	\$418	\$513
Labor	\$14	\$15	\$18	\$20	\$18	\$20	\$18	\$20
Labor Overhead @ 40%	\$6	\$6	\$7	\$8	\$7	\$8	\$7	\$8
Supplier Markup @ 29% ***	\$13	\$15	\$16	\$19	\$15	\$17	\$16	\$19
Manufacturer Cost	\$358	\$428	\$460	\$560	\$400	\$479	\$460	\$560
Manufacturer Carrying Cost @ 4%	\$14	\$17	\$18	\$22	\$16	\$19	\$18	\$22
Total Cost to Dealer	\$372	\$445	\$478	\$582	\$416	\$498	\$478	\$582
Incremental Cost			\$106	\$137			\$62	\$84

*2.5 L bricks; use C=\$4.67V+\$1.50 (Arcadis, 9/30/99) with the \$1.50 applied per 2.5L brick (Note: C is cost to mfr, thus not marked up in tables).

**Baseline from 2005 FRM RIA; 2008 from Arcadis 9/30/98.

***Not applied to precious metals or Substrate (substrate costs already include supplier markup).

****From 2005 FRM RIA and Arcadis, 9/30/98.

b. Oxygen Sensors

Largely because we expect catalyst configurations to change, we expect oxygen sensor usage to change. Oxygen sensors are used both for fuel control and for OBD catalyst monitoring. Therefore, different catalyst configurations would likely result in different oxygen sensor usage. For 2005, we assume that 13 percent of heavy-duty gasoline vehicles and engines will employ dual heated oxygen sensors, and 87 percent will employ four heated oxygen sensors. For 2008, we assume that all vehicles and engines will use four heated oxygen sensors, with two of those being fast light-off sensors for better cold start performance. We have estimated the cost of a heated oxygen sensor at \$20 per sensor, and a fast light-off sensor at \$28 per sensor.

c. Exhaust Gas Recirculation (EGR)

Electronically controlled EGR is currently used on about 85 percent of non-California gasoline heavy-duty vehicles. The percentage of the fleet with EGR is not expected to change as a result of the 2005 standards. For 2008, we assume that 100 percent of vehicles and engines will use electronically controlled EGR. In addition, some minor changes in control algorithms may be necessary to improve upon EGR performance. These changes are expected to cost from \$5 to \$12 per vehicle. For this analysis, we have used a cost of \$10 per vehicle, applied only to those 15 percent adding EGR for 2008.

d. Secondary Air Injection with Closed Loop Control

The hardware cost for vehicles which use secondary air injection to reduce HC and CO emissions is estimated to be about \$65 per vehicle. For 2005, we estimate a secondary air injection usage rate of 30 percent on vehicles and 50 percent on engines. For 2008, we estimate that 50 percent of vehicles will use secondary air injection, while the percentage of engines using it will remain at 50 percent.

e. Exhaust Systems

We expect that heat managed exhaust systems will be used on some applications to improve catalyst light-off time. Heat managed exhaust systems can include any combination of thin walled components or otherwise low thermal-capacity components, air gapped components, insulation, etc. We estimate that such systems will cost \$40 per vehicle when they are used. For 2005, we estimate that they will be used on 40 percent of the vehicles, and none of the engines. For 2008, we estimate that they will be used on 60 percent of vehicles and engines having a dual close-coupled with a dual underfloor catalyst system, and 100 percent of vehicles and engines having only a dual underfloor catalyst system.

f. Evaporative Emission Control Systems

There are two approaches to reducing evaporative emissions for a given fuel. One is to minimize the potential for permeation and leakage by reducing the number of hoses, fittings and connections. The second is to use less permeable hoses and lower loss fittings and connections. Manufacturers are already employing both approaches. The 2008 evaporative emission standards will not require the development of new materials or, in many cases, even the new application of existing materials. Low permeability materials and low loss connections and seals are already used to varying degrees on current vehicles.

In our proposal, we estimated the cost associated with our new evaporative standards at \$4 per vehicle. However, we received comments that our \$4 per vehicle cost was not appropriate for heavy-duty gasoline vehicles. Those comments suggested the cost would be as high as \$32 to \$45 per vehicle, with claims that a new canister array, a returnless fuel system, an upgrade of fuel system materials, and possible air inlet control measures would be needed.

The \$4 estimate used in our proposal was developed for light-duty applications under our Tier 2 cost analysis.³⁰ Given that the Tier 2 estimate was for light-duty applications, it may represent an under estimate of the cost for heavy-duty applications. Despite the fact that most heavy-duty gasoline vehicles currently can meet the emission levels being finalized, we believe that manufacturers will improve upon their designs so as to improve upon compliance margins.

We also believe that the \$32 to \$45 cost estimate supplied via comment represents a worst case estimate rather than an average cost that can be applied across the HD gasoline fleet. Therefore, we have increased our estimated cost from \$4 to \$21 to represent a conservative estimate of the typical cost. The \$21 estimate is a middle ground estimate appropriate for application to the entire heavy-duty gasoline fleet. This seems reasonable considering the \$4 cost at the lighter end of the range where vehicles are similar to the Tier 2 MDPVs, and the \$32 to \$45 cost for vehicles at the heavier end of the range where larger fuel tanks and longer fuel lines present more challenge. This \$21 cost is applied to all heavy-duty gasoline vehicles and engines for the purpose of estimating the overall cost of the new standards regardless of their current emission levels.

g. Summary of Technology/Hardware Costs

The costs associated with technology, or hardware, are summarized in Table V.B-4.

Table V.B-4. Summary of Hardware Costs for the Proposed 2007 Heavy-Duty Gasoline Standards

	2005 Vehicle		Complete Vehicles 2008 Vehicle		Increment		2005 Engine		Incomplete Vehicles 2008 Engine		Increment	
	Standard System	Larger System	Standard System	Larger System	Standard System	Larger System	Standard System	Larger System	Standard System	Larger System	Standard System	Larger System
Catalyst Costs	\$360	\$432	\$470	\$574	\$110	\$141	\$400	\$480	\$470	\$574	\$70	\$94
Oxygen Sensors	\$75	\$75	\$96	\$96	\$21	\$21	\$77	\$77	\$96	\$96	\$19	\$19
EGR	\$9	\$9	\$10	\$10	\$2	\$2	\$9	\$9	\$10	\$10	\$2	\$2
Heat Managed Exhaust*	\$16	\$16	\$32	\$32	\$16	\$16	\$0	\$0	\$32	\$32	\$32	\$32
Secondary Air Injection with Closed Loop Control	\$20	\$20	\$33	\$33	\$13	\$13	\$33	\$33	\$33	\$33	\$0	\$0
Evap System Improvements	\$0	\$0	\$21	\$21	\$21	\$21	\$0	\$0	\$21	\$21	\$21	\$21
Total Dealer Cost	\$479	\$551	\$661	\$765	\$183	\$214	\$518	\$598	\$661	\$765	\$143	\$167
Dealer Carrying Cost @ 3%	\$14	\$17	\$20	\$23			\$16	\$18	\$20	\$23		
Total Cost to the Consumer	\$493	\$568	\$681	\$788			\$534	\$616	\$681	\$788		
Increased Cost to the Consumer					\$188	\$220					\$147	\$172

*May include air gaps, thin walls, low thermal capacity manifold, insulation, etc.

Note: Some values may not add up precisely due to rounding.

As Table V.B-4 shows, the incremental technology costs for heavy-duty gasoline vehicles and engines associated with the 2008 standards are \$188 and \$220 for standard and large sized engines in vehicle-based applications, respectively, and \$147 and \$172 for standard and large sized engines in engine-based applications, respectively.

Weighting these costs assuming a standard/large split of 75/25 percent, gives incremental costs of \$196 for complete vehicles and \$153 for incomplete vehicles. For the long-term, there are factors we believe are likely to reduce the costs to manufacturers. As noted below, we project fixed costs to be recovered by manufacturers during the first five years of production, after which they would expire. For variable costs, research in the costs of manufacturing has consistently shown that as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts. These effects are often described as the manufacturing learning curve as described in Chapter V.A.6 of this Regulatory Impact Analysis.

We applied a p value of 80 percent in this analysis. Using one year as the base unit of production, the first doubling would occur at the start of the third model year of production. Beyond that time, we did not incorporate further cost reductions due to the learning curve. This differs from the heavy-duty diesel cost analysis where we did apply the learning curve beyond the third year. We applied the learning curve reduction only once for gasoline because we anticipate that, for the most part, the 2008 heavy-duty standards would be met through improvements to existing technologies rather than through the use of new technologies. With existing technologies, there would be less opportunity for lowering production costs.

In addition, we did not apply the learning curve to the catalyst precious metal costs due to the uncertainty of future precious metal prices. Although manufacturers may be able to reduce the use of precious metals through factors consistent with the application of the learning curve, the future price of precious metals is highly uncertain. Any savings due to a reduction in the amount of precious metals used for a catalyst system could be overcome by increased precious metal unit costs. Also, we have not applied the learning curve to evaporative emission control system costs.

Therefore, as a result of the learning curve, the variable costs per vehicle, minus the precious metal costs, would decrease by 20 percent beginning in the 2010 model year. Thereafter, the incremental technology costs would fall to \$179 and \$138 for vehicles and engines, respectively.

4. Heavy-Duty Gasoline Fixed Costs

The fixed costs are broken into four main components: research and development, tooling, certification, and in-use testing. These costs are discussed individually in the following sections.

a. R&D and Tooling Costs

The 2008 vehicle-based standards will essentially require the application of California LEV-II and Tier 2 technology to heavy-duty gasoline vehicles nationally. Since this technology is being developed in response to those rules, we are assuming that considerable carry-across will occur from those R&D efforts to the heavy-duty gasoline systems. R&D primarily includes engineering staff time and development vehicles. A large part of the research effort will be evaluating and selecting the appropriate mix of emission control components and optimizing those components into a system capable of meeting the 2008 standards. It also includes engine modifications where necessary and air/fuel ratio calibration work. Manufacturers will take differing approaches in their research programs. In our Tier 2 analysis, we assumed an R&D cost of \$5 million per vehicle line estimating that this would cover about 25 engineering staff person years and about 20 development vehicles.^f We estimated such a large R&D effort because calibration and system optimization was expected to be a critical part of the effort to meet the Tier 2 standards. However, we believe those R&D costs are likely overstated for purposes here because the projection ignores the carryover of knowledge from the first vehicle lines designed to meet the standard to others phased-in later. For this heavy-duty gasoline analysis, we assume an R&D cost of \$2.5 million per line due to the carryover from Tier 2 and LEV II R&D efforts.

According to 2000 model year certification data, there is one engine family certified as an incomplete vehicle federally with no corresponding engine certified for sale in California. We have assumed that engine will require R&D efforts to comply with today's proposed standards. We have also assumed that four other engines (those having six liters or more displacement typically used in larger applications) currently being certified to engine standards will continue to be so certified and will require R&D efforts to comply with today's engine standards. That gives four more engines requiring R&D efforts, for a total of five engines to which we have applied the \$2.5 million R&D cost.

In our Tier 2 analysis and our proposal, we estimated tooling costs at \$2 million per line. Tooling costs include facilities modifications necessary to produce and assemble components and vehicles meeting the new standards. We believe that this is a reasonable estimate based on engineering judgement and review of previous estimates of tooling costs for emissions control components.³¹ We have applied tooling costs only to those engines requiring R&D efforts.

^f This estimate is based on staff cost of \$60 per hour and development vehicle cost of \$100,000 per vehicle line.

R&D costs are spread out evenly over the three year period prior to the first year of implementation and grown at a seven percent rate. Tooling costs are assumed to occur one year prior to implementation and are grown for one year at a seven percent rate. These costs are then amortized over a five year period following implementation, again at a seven percent rate. This results in R&D and tooling costs of just over \$9 per complete vehicle and \$23 per incomplete vehicle. The costs are higher for the incomplete vehicles because of the lower sales over which to spread the same total costs as estimated for complete vehicles. These costs become zero five years after implementation because we assume the costs will have been recovered.

b. Certification Costs

Manufacturers incur an annual cost as part of certification and compliance and would incur those costs without any change to the standards. However, we allow manufacturers to carry-over some data generated for certification when vehicles are not significantly changed from one model year to the next. This test data is generated to demonstrate vehicle emissions levels and emissions durability. Due to the new standards, such data will have to be generated for the new 2008 model year vehicles rather than being carried-over from previous model years. Therefore, we believe it is appropriate to include the cost of generating new emissions test and durability data. We have estimated certification costs at \$30,000 per engine family.³² This estimate does not account for the ability of manufacturers, in most cases, to carry-over certification data from California certified systems. Such a practice would lower certification costs.

We have applied the certification cost to the 17 complete and 26 incomplete engine families, the number certified for the 2000 model year. Certification costs would be incurred, on average, one year before the start of production. Thus, this cost is increased at a rate of seven percent for one year and applied to the appropriate vehicle certifications and engine certifications. The costs are then amortized over five years and divided by the appropriate complete and incomplete sales projections. This results in projected per-vehicle certification costs of \$0.42 for complete vehicle configurations and \$1.59 for incomplete vehicle configurations during the first five years of the program. After five years, the certification costs become zero as manufacturers fall into their normal practice of carrying-over data from one year to the next.

5. Summary of Heavy-Duty Gasoline Costs

Table V.B-5 contains a summary of per-vehicle costs associated with the 2008 standards for heavy-duty gasoline vehicles and engines. The hardware cost components include a part or emission control system supplier markup of 29 percent, and both manufacturer and dealer carrying costs of four percent and three percent, respectively. The costs are presented as incremental cost increases from the 2005 system costs.

Table V.B-5. Summary of Incremental Costs to Meet the 2008 Heavy-Duty Gasoline Emission Standards

		<i>Complete Vehicles</i>	<i>Incomplete Vehicles</i>	<i>HDGVs</i>
Near Term	Technology/Hardware	\$196	\$153	\$184
	Fixed Costs	\$10	\$25	\$14
	Incremental Cost	\$206	\$178	\$198
Long Term	Technology/Hardware	\$179	\$138	\$167
	Fixed Costs	\$0	\$0	\$0
	Incremental Cost	\$179	\$138	\$167

6. Total Nationwide Costs for 2008 Heavy-Duty Gasoline Vehicles

The above analyses developed incremental per vehicle manufacturer and consumer cost estimates for heavy-duty gasoline vehicles designed to the new Phase 2 gasoline standards. With data for the current size and characteristics of the vehicle fleet and projections for the future, we have translated these per vehicle costs into estimated total annualized costs to the nation for the new Phase 2 gasoline standards. Table V.B-6 presents the results of this analysis.

To prepare these estimates, we projected sales for heavy-duty gasoline vehicles. We estimated current vehicle sales based on 1996 sales data submitted by vehicle manufacturers as part of certification. These sales correlated reasonably well with other available sales information. We assumed a mix of 71 percent complete vehicles and 29 percent incomplete vehicles based on these sales data, excluding an estimated 70,000 units counted in the Tier 2 analysis as medium-duty passenger vehicles. California sales were excluded from this analysis because California emissions standards apply to those vehicles. We have projected vehicle sales to grow two percent from 1996 through 2007, then at a constant number of vehicles (two percent of 1996 sales) for each year thereafter. Table V.B-6 contains those sales projections.

Table V.B-6. Estimated Annualized Nationwide Vehicle Costs Associated with the 2008 Heavy-Duty Gasoline Emission Standards

Year	Projected Sales	Fixed Costs	Fraction of Fleet Complying	Variable Costs	Operating Costs	Total Cost	Per Vehicle Cost
2007	424,560	\$0	0%	\$0	\$0	\$0	\$0
2008	431,520	\$6,213,290	50%	\$39,635,728	\$0	\$45,849,018	\$213
2009	438,480	\$6,213,290	100%	\$73,362,727	\$0	\$79,576,017	\$181
2010	445,440	\$6,213,290	100%	\$74,527,215	\$0	\$80,740,505	\$181
2011	452,400	\$6,213,290	100%	\$75,691,703	\$0	\$81,904,993	\$181
2012	459,360	\$6,213,290	100%	\$76,856,190	\$0	\$83,069,481	\$181
2013	466,320	\$0	100%	\$78,020,678	\$0	\$78,020,678	\$167
2014	473,280	\$0	100%	\$79,185,166	\$0	\$79,185,166	\$167
2015	480,240	\$0	100%	\$80,349,654	\$0	\$80,349,654	\$167
2016	487,200	\$0	100%	\$81,514,141	\$0	\$81,514,141	\$167
2017	494,160	\$0	100%	\$82,678,629	\$0	\$82,678,629	\$167
2018	501,120	\$0	100%	\$83,843,117	\$0	\$83,843,117	\$167
2019	508,080	\$0	100%	\$85,007,604	\$0	\$85,007,604	\$167
2020	515,040	\$0	100%	\$86,172,092	\$0	\$86,172,092	\$167
2021	522,000	\$0	100%	\$87,336,580	\$0	\$87,336,580	\$167
2022	528,960	\$0	100%	\$88,501,068	\$0	\$88,501,068	\$167
2023	535,920	\$0	100%	\$89,665,555	\$0	\$89,665,555	\$167
2024	542,880	\$0	100%	\$90,830,043	\$0	\$90,830,043	\$167
2025	549,840	\$0	100%	\$91,994,531	\$0	\$91,994,531	\$167
2026	556,800	\$0	100%	\$93,159,019	\$0	\$93,159,019	\$167
2027	563,760	\$0	100%	\$94,323,506	\$0	\$94,323,506	\$167
2028	570,720	\$0	100%	\$95,487,994	\$0	\$95,487,994	\$167
2029	577,680	\$0	100%	\$96,652,482	\$0	\$96,652,482	\$167
2030	584,640	\$0	100%	\$97,816,970	\$0	\$97,816,970	\$167
2031	591,600	\$0	100%	\$98,981,457	\$0	\$98,981,457	\$167
2032	598,560	\$0	100%	\$100,145,945	\$0	\$100,145,945	\$167
2033	605,520	\$0	100%	\$101,310,433	\$0	\$101,310,433	\$167
2034	612,480	\$0	100%	\$102,474,920	\$0	\$102,474,920	\$167
2035	619,440	\$0	100%	\$103,639,408	\$0	\$103,639,408	\$167

As shown in Table V.B-6, we have projected a total cost starting at \$46 million in 2008 and peaking at \$83 million in 2012. In 2013, the costs decrease due to the elimination of fixed costs. Thereafter, costs gradually increase with projected sales. Operating costs are \$0 because the technologies expected should have no impact on fuel economy or maintenance costs. The calculated total costs represent a combined estimate of fixed costs, as they are allocated over fleet sales during the first five years of sale, and variable costs assessed at the point of sale. These costs include exhaust and improved evaporative control systems. These estimates do not include costs due to improved fuel quality, which were presented in the Tier 2 Regulatory Impact Analysis for gasoline.³³

Table V.B-7 shows the non-annualized costs.

Table V.B-7. Estimated Non-Annualized Nationwide Vehicle Costs Associated with the 2008 Heavy-Duty Gasoline Emission Standards

Year	Projected Sales	Fixed Costs	Fraction of Fleet		Operating Costs	Total Cost
			Complying	Variable Costs		
2004	403,680	\$0	0%	\$0	\$0	\$0
2005	410,640	\$4,166,667	0%	\$0	\$0	\$4,166,667
2006	417,600	\$4,166,667	0%	\$0	\$0	\$4,166,667
2007	424,560	\$14,946,667	0%	\$0	\$0	\$14,946,667
2008	431,520	\$0	50%	\$39,635,728	\$0	\$39,635,728
2009	438,480	\$0	100%	\$73,362,727	\$0	\$73,362,727
2010	445,440	\$0	100%	\$74,527,215	\$0	\$74,527,215
2011	452,400	\$0	100%	\$75,691,703	\$0	\$75,691,703
2012	459,360	\$0	100%	\$76,856,190	\$0	\$76,856,190
2013	466,320	\$0	100%	\$78,020,678	\$0	\$78,020,678
2014	473,280	\$0	100%	\$79,185,166	\$0	\$79,185,166
2015	480,240	\$0	100%	\$80,349,654	\$0	\$80,349,654
2016	487,200	\$0	100%	\$81,514,141	\$0	\$81,514,141
2017	494,160	\$0	100%	\$82,678,629	\$0	\$82,678,629
2018	501,120	\$0	100%	\$83,843,117	\$0	\$83,843,117
2019	508,080	\$0	100%	\$85,007,604	\$0	\$85,007,604
2020	515,040	\$0	100%	\$86,172,092	\$0	\$86,172,092
2021	522,000	\$0	100%	\$87,336,580	\$0	\$87,336,580
2022	528,960	\$0	100%	\$88,501,068	\$0	\$88,501,068
2023	535,920	\$0	100%	\$89,665,555	\$0	\$89,665,555
2024	542,880	\$0	100%	\$90,830,043	\$0	\$90,830,043
2025	549,840	\$0	100%	\$91,994,531	\$0	\$91,994,531
2026	556,800	\$0	100%	\$93,159,019	\$0	\$93,159,019
2027	563,760	\$0	100%	\$94,323,506	\$0	\$94,323,506
2028	570,720	\$0	100%	\$95,487,994	\$0	\$95,487,994
2029	577,680	\$0	100%	\$96,652,482	\$0	\$96,652,482
2030	584,640	\$0	100%	\$97,816,970	\$0	\$97,816,970
2031	591,600	\$0	100%	\$98,981,457	\$0	\$98,981,457
2032	598,560	\$0	100%	\$100,145,945	\$0	\$100,145,945
2033	605,520	\$0	100%	\$101,310,433	\$0	\$101,310,433
2034	612,480	\$0	100%	\$102,474,920	\$0	\$102,474,920
2035	619,440	\$0	100%	\$103,639,408	\$0	\$103,639,408

C. Diesel Fuel Costs

In this section, we first lay out the methodology for our analysis of the cost of desulfurizing highway diesel fuel. Then we present the estimated cost of desulfurizing highway diesel fuel.

1. Methodology

a. Overview

For the proposed rule, we estimated the cost of desulfurizing highway diesel fuel to meet a 15 ppm cap sulfur standard based on a characteristic refinery, which was sized to represent the average cost for all U.S. refineries. Although we felt confident in the cost estimates made with this model, the analysis did not allow us to adequately address certain issues, particularly the comments which we received concerning the future supply of highway diesel fuel. For this final rule, we expanded upon our analysis to allow us to better understand the range of situations faced by refiners to supply highway diesel fuel. This section presents an overview of our expanded cost analysis.

Our cost estimate for desulfurizing diesel fuel is based on hydrotreating process operations and capital cost information received from two licensors of conventional distillate[§] desulfurization technology. In addition, information obtained from two other vendors of diesel desulfurization technology further corroborated the information provided by the first two vendors. The costs for desulfurizing diesel fuel were estimated for each refinery in the country which was producing highway diesel fuel during 1998 and 1999. Each refinery's production volumes were projected to 2006 using a ratio of the projected consumption of highway diesel fuel in 2006 by EIA versus the production in 1998 and 1999. We presume that each refinery producing highway diesel fuel starts with a highway diesel fuel sulfur level of about 340 ppm and reduces it to between 5 to 10 ppm, or 7 ppm on average. We believe that refiners would have to desulfurize their diesel fuel to about 7 ppm to reliably and continually meet the proposed 15 ppm cap standard. Construction and operating cost factors and utility costs for each refinery are based on values calculated for each PADD and are applied to all the refineries operating in that PADD. For each refinery we estimated the fraction of straight run distillate, light cycle oil (LCO), and other cracked stocks (coker, visbreaker, thermal cracked) in the highway diesel fuel, and the cost to desulfurize each of those stocks. The average desulfurization cost for each refinery was based on the volume-weighted average of desulfurizing each of those blendstocks. We based our cost estimate on the premise that the refining industry will be able to revamp 80 percent of the

[§] Distillate refers to a broad category of fuels falling into a specific boiling range. Distillate fuels have a heavier molecular weight and therefore boil at higher temperatures than gasoline. Distillate includes diesel fuel, jet fuels, kerosene and home heating oil.

existing diesel hydrotreater capacity, while the other 20 percent will have to install brand new “grassroots” units. Since we do not know which refineries would install revamps units and which would install grassroots units, we calculated the revamp and grassroots cost for each refinery, and based 80 percent of the cost on the revamped cost, and 20 percent on the grassroots cost. For determining the grassroots cost of a refinery currently producing highway diesel fuel, we used the operating cost of a revamped unit and the capital cost of a grassroots unit. Using the operating cost of a revamped unit is appropriate because that refinery is incurring operating cost now for meeting the current 500 ppm sulfur highway diesel fuel standard.

The final rule provides the refining industry a temporary compliance option which refiners them to continue selling up to about 20 percent of the highway diesel pool at this higher sulfur level until 2010, at which point all highway diesel fuel must meet the 15 ppm cap sulfur standard. We estimated the cost of refiners using this option based on the assumption that the refineries which can meet the 15ppm cap sulfur standard at the lowest cost will meet the requirements in 2006. The balance of refineries are presumed hold off making their investments to meet the 15 ppm sulfur standard until 2010.

We received a number of comments from the refining industry which suggested that some refiners may choose to partially or completely leave the highway diesel fuel market which could result in a shortfall in highway diesel fuel supply. Arguably, the refiners which are most likely to exit the highway diesel market would be those which are facing the highest cost to desulfurize their highway diesel fuel. Those most likely to maintain highway production, or even expand production to fill market demand would be the lowest cost producers. In some cases a portion of the market demand for 15 ppm sulfur highway diesel fuel could be met by today’s predominant or exclusive producers of nonhighway diesel fuel. To understand this possibility, we assessed the cost to offhighway diesel fuel producers of desulfurizing their offhighway diesel fuel to make up a potential supply shortfall in highway diesel fuel. In fact, current highway diesel fuel producers which decide they must install a grassroots unit to meet the 15 ppm cap standard would have no advantage over current nonhighway producers producing a similar volume of fuel and processing a similar type of crude oil. The cost analysis allowing for such production shifts between diesel fuel markets by refineries is presented as a sensitivity analysis further below.

Finally, the cost of desulfurizing diesel fuel to meet the 15 ppm cap standard was estimated by several other entities. Mathpro provided estimates for the Engine Manufacturers Association. The National Petroleum Council used the Mathpro estimates and adjusted them based on some concerns which they had on costs. The American Petroleum Institute funded a study by Charles River and Baker and O’Brien to study this issue. Finally, the Department of Energy hired Ensys to estimate the cost of meeting the 15 ppm cap standard. These various cost studies are summarized at the end of this section and the cost estimates are compared to our costs if an appropriate comparison can be made.

The analyses and discussion associated with these issues is contained in the following sections.

b. Derivation of the Fraction of LCO and other Cracked Blendstocks in Highway Diesel Fuel for Each Refinery

In Chapter IV, we established that an important challenge for refiners in meeting the proposed 15 ppm sulfur cap was the LCO fraction of their highway diesel fuel pool. Thus, the first step in segregating refineries according to the difficulty of desulfurization is to estimate each refinery's LCO fraction of their highway diesel fuel pool. This data is generally not publically available, so we estimated these fractions from other sources of information.

First, estimates of the volumes of high and low sulfur distillate produced in the last half of 1998 and the first half of 1999 by each U.S. refinery were obtained from the Energy Information Administration (EIA). According to EIA, U.S. refiners produce a total of 49 billion gallons of distillate per year, with 32 billion gallons (about 65 percent) of that being low sulfur diesel fuel. We determined that highway diesel fuel is produced by 121^h different refineries throughout the U.S.

Second, we estimated the volume of LCO produced by each refinery using information from the Oil and Gas Journal (OGJ).³⁴ The OGJ publishes information on the capacity of major processing units for each refinery in the country, including the FCC unit. We assumed that FCC units operate at 90 percent of capacity, which is consistent with the API/NPRA survey of Refining Operations and Product Quality.³⁵ We first assumed that 17 percent of the feedstock volume to the FCC unit is converted into LCO based on confidential information shared with EPA by a vendor of fluidized cat cracker units. Next we assumed that refineries with distillate hydrocrackers send their LCO to the distillate hydrocracker and convert it to gasoline.

Furthermore, FCC feed hydrotreaters can affect the sulfur level and the treatability of light cycle oil. FCC feed hydrotreaters hydrotreat the gasoil fed to the FCC unit, usually at a pressure much higher than distillate hydrotreaters. The resulting cracked blendstock from the FCC unit is much lower in sulfur, and, most important, some of the sterically hindered compounds are desulfurized. However, only high pressure feed hydrotreaters (i.e., 1500 psi units) can convert a significant portion of these sterically hindered compounds.³⁶ We don't have

^h There are four refineries in Alaska producing diesel fuel which is exempted from the current 500 ppm sulfur cap standard for highway diesel fuel. Consequently, the diesel fuel they produce is used for both highway and offhighway purposes without regard to the end use. Since only an estimated 5 percent of diesel fuel in Alaska is consumed in highway applications, for our cost analysis we assumed only one would, in the future, produce highway diesel fuel to supply demand. Thus, we also included that one refinery in this analysis of blendstock quality.

any specific information on what fraction of these hydrotreaters are high pressure, however, industry experts estimated that about 20 percent of the FCC feed hydrotreaters are high pressure, with most or all of these being in California. Since we don't know which feed hydrotreaters are high pressure, we conservatively presume that only the California feed hydrotreaters are high pressure. Since most California refineries already have distillate hydrocrackers, the fact that they have high pressure feed FCC hydrotreaters is a moot point and does not affect the fraction of LCO of these refineries. Consequently, we have not made any adjustments in our cost methodology to account for the presence of FCC feed hydrotreaters.

Based on these assumptions, we calculated the fraction of LCO to total distillate production to be about 15 percent. To independently check this estimate, we compared our estimate of the LCO fraction of total distillate production with that reported in the API/NPRA survey. The API/NPRA survey shows that, on average for the U.S. refining industry as a whole, light cycle oil comprises about 21 percent of number two distillate. For highway diesel fuel, the API/NPRA Survey shows the percentage of LCO to the total pool of highway diesel fuel to be 22 percent, and both of these percentages are much higher than our initial estimate. In our distillate production model, if we increase the fraction of FCC feedstock converted to LCO from 17 percent to 25 percent, our model matches the fraction of LCO to distillate shown by the API/NPRA survey for the highway diesel pool. Thus, we used 25 percent for the ratio of LCO product to FCC feed in our refinery model.

Applying these assumptions using the EIA and OGJ information, we calculated the fraction of LCO relative to the total distillate production for each refinery. We then categorized the refineries based on the fraction of their distillate pool which is LCO at 5 or 10 percent intervals from 0 to 60 percent. The distribution of refineries by fraction of LCO is summarized in Table V.C-1.

Table V.C-1. Presence of Light Cycle Oil in the Distillate of U.S. Refineries Producing Highway Diesel Fuel

	<i>Percentage of LCO in the Distillate Pool</i>								
	0%	<10%	<15%	<20%	<25%	<30%	<40%	<50%	<60%
Number of Refineries	49	51	54	59	71	93	113	116	118
Cumulative Percentage of US Highway Diesel Volume	27	29	32	36	47	77	95	98	99

In Table V.C-1, our analysis shows that distillate contains anywhere from no LCO to 60 percent LCO. Our analysis also shows that 49 U.S. refineries which produce about 27 percent of the distillate in the U.S. blend no LCO into this distillate, while the distillate from the remaining 72 refineries averages about about 28 percent LCO by volume. This is important because of the large difference in fractions of LCO in the highway diesel pool for the U.S refining industry. Refineries which blend no LCO into their distillate pool do so because they either do not have an FCC unit, or because they have a distillate hydrocracker which is used to “upgrade” their LCO to gasoline. Refineries with LCO in their distillate have an FCC unit, and they likely do not have a hydrocracker. The refineries in both groups have distillate hydrotreaters for producing onhighway diesel fuel for meeting the current 500 ppm cap standard.

We also estimated the fraction of other cracked stocks, which includes coker, thermally cracked and visbreaker distillate, in each refinery’s distillate fuel. We first estimated the volume of these other cracked stocks produced by each refinery using information from the Oil and Gas Journal (OGJ). Similar to how we calculated the fraction of LCO, we assumed that delayed and fluid cokers, visbreakers, and thermal crackers all operate at 90 percent of capacity. Based on a conversation with a refining industry consultant, we assumed that 30 percent of delayed coker and 15 percent of the other units’ product is distillate blended into the distillate pool. Unlike LCO, we do not assume that refineries with hydrocrackers send their other cracked stocks to the hydrocracker for conversion to gasoline. While most refineries probably do not send their other cracked stocks to their hydrocracker, it is also likely that some do for at least some of their other cracked stocks, so our assumption is probably somewhat conservative. After analyzing each refinery’s other cracked stock distillate production and averaging that production over the entire industry, we estimate that about 8 percent of the entire highway diesel fuel volume is comprised of these other cracked stocks. This value agrees well with the API/NPRA survey.³⁷

Table V.C-2. Presence of Other Cracked Blendstocks in the Distillate of U.S. Refineries Producing Highway Diesel Fuel

	<i>Percentage of Other Cracked Stocks in the Distillate Pool</i>							
	0%	<10%	<15%	<20%	<25%	<30%	<40%	<50%
Number of Refineries	89	95	103	111	112	118	120	121
Cumulative Percentage of US Highway Diesel Volume	55	67	77	88	89	95	100	100

As depicted in Table V.C-2, our analysis shows that over half of distillate fuel in the U.S, which is produced by 89 refineries, does not contain other cracked stocks from cokers, visbreakers and thermal crackers. Of the refineries which are projected to blend other cracked stocks into their distillate pool, we estimate that, on average, the distillate from these refineries contains approximately 18 percent of other cracked stocks.

Next we set out to determine the cost of desulfurizing highway diesel fuel. We met with Criterion Catalyst/ABB Lummus, UOP, Akzo Nobel and Haldor Topsoe and a number of refiners. One of these vendors provided diesel desulfurization unit operation and capital cost information for different levels of LCO in diesel fuel, which included none, 15 percent, 23 percent and 30 percent, and varying amounts of coker distillate. Another vendor provided significant cost information for 25 percent LCO in diesel fuel, and 10 percent coker distillate. In addition, information from the other two vendors helped to corroborate the operating and cost information obtained from the first two vendors. This information provided by these vendors allowed us to estimate the cost of desulfurizing the different diesel fuel blendstocks.

The information provided by the vendors is based on typical diesel fuels, however, in reality diesel fuel (especially LCO, and to a lesser degree other cracked stocks) varies in desulfurization difficulty based on the amount of sterically hindered compounds present in the fuel, which is determined by the endpoint of diesel fuel, and also by the type of crude oil being refined. The vendors provided cost information based on diesel fuels with T-90 distillation points which varied from 605 °F to 630 °F, which would roughly correspond to distillation endpoints of 655 °F to 680 °F. These endpoints can be interpreted to mean that the diesel fuel would, as explained in Chapter IV above, contain sterically hindered compounds. However, a summertime diesel fuel survey for 1997 shows that the endpoint of highway diesel fuel varies from 600 °F to 700 °F, thus the lighter diesel fuels would contain no sterically hindered

compounds, and the heavier diesel fuels would contain more.³⁸ Our analysis attempts to capture the cost for each refinery to produce highway diesel fuel which meets the 15ppm cap sulfur standard, however, we do not have specific information for how the highway diesel endpoints vary from refinery to refinery, or from season to season.

Similarly, we do not have information on what type of crude oil is being processed by each refinery as the quality of crude oil being processed by a refinery affects the desulfurization difficulty of the various diesel fuel blendstocks. For example, North Slope crude oil from Alaska contains a higher fraction of aromatic compounds than most other crude oils.³⁹ If the highway diesel fuel produced from Alaskan crude oil has a high endpoint, the highway diesel fuel would be expected to contain more sterically hindered compounds compared to another diesel fuel produced from a lighter crude oil, such as Western Texas Intermediate, with the same endpoint and the same mix of cracked stocks.

As discussed in Chapter IV, refiners which are producing their highway diesel fuel with a higher endpoint and refining heavier, more aromatic crude oils, they are doing so with an economic incentive. The economic incentive is that those heavier, more sour crude oils are 1 to 2 dollars per barrel less expensive than lighter, sweeter crude oils. Also, if the heaviest fraction of highway diesel fuel containing the sterically hindered compounds earns at least 10 dollars per barrel (about 25 c/gal) more when it has been upgraded and blended into highway diesel fuel instead of the most likely alternative, which is to be sold in the resid market.⁴⁰ In sum, diesel fuel processed by a particular refiner can either be easier or more difficult to treat than what we estimate depending on how their diesel fuel endpoint compares to the average endpoint of the industry, and depending on the crude oil used. For a nationwide analysis, it is appropriate to base our cost analysis for each refinery on what we estimate would be typical or average qualities for each diesel fuel blendstock. Some estimates of individual refinery costs will be high, others will be low, but be representative on average.

c. Technology and Cost Inputs from Vendors

The most significant cost involved in meeting a more stringent diesel sulfur standard would be the cost of constructing and operating the distillate desulfurization unit. For estimating the cost of building and operating these units, we obtained detailed information on the raw material and utility needs, the capital costs and the desulfurization capabilities from licensors of two different desulfurization technologies.^{41 42 43} Each vendor provided most of the information needed to allow us to cost out a retrofit to an existing desulfurization unit, and also cost out the building of a new desulfurization unit from grass roots. We also met with two other vendors of desulfurization technology, though they did not provide enough information to develop an independent cost estimate.

In addition to the information which we obtained directly from the vendors, we reviewed the vendor submissions made to the National Petroleum Council (NPC) by Akzo Nobel, Criterion, Haldor Topsoe, UOP and IFP.⁴⁴ Of the five vendors which provided information to the NPC; we met with all of them except IFP. These vendors provided information for retrofitting existing diesel hydrotreaters and many of them also provided information on the combined operations of the existing hydrotreater and the revamp together. The full set of submissions made to the NPC allowed us to compare all these vendor's information to each other on the same basis. With one exception, these submissions corroborated the costs we had developed earlier. In one case, though, the vendor's information suggested that a significant amount of hydrogen would be consumed to remove the sulfur, which would also cause a significant increase in API gravity (the diesel fuel would be made less dense). However, the other vendors' information indicated that the sulfur can be removed from diesel fuel without dramatic differences in diesel fuel quality, and with only a modest amount of hydrogen consumption. Thus, we based our estimate of hydrogen consumption on the estimates of hydrogen consumption, as reflected by the majority of the vendors. Conversely, API has indicated that they believe that very high hydrotreating pressures (e.g., 1200 psi or more) will be necessary to meet a 15 ppm cap standard, although their contractor for their cost study indicated that pressures under 1000 psi would be adequate. None of the vendors projected that pressures more than 900 psi would be necessary and most of the vendors projected that 650 psi would be sufficient. Likewise, a number of refiners have indicated that pressures well below 1000 psi would be sufficient. Thus, we based our estimate of capital cost on two different vendor submissions which were based on units operating at 650 and 900 psi pressure.

Since refineries already have a distillate hydrotreater in place to desulfurize highway diesel fuel down to under 500 ppm, the vendors concluded that it would only be necessary to retrofit an existing diesel hydrotreating unit with a number of different vessels, such as a reactor, a hydrogen compressor, a recycle scrubber an interstage stripper and other associated process hardware. Despite the fact that each vendor is basing their cost information on retrofits, the two vendors who provided us information on our cost analysis, still differed in individual cost elements due to differences in the capital equipment used, although the overall cost ended up being roughly the same.

The differences in the estimated capital and operating costs between the two vendors is largely due to the differences in technical approaches assumed by each vendor for meeting the proposed diesel sulfur standards. One vendor, which we will call Vendor A,ⁱ chose to estimate

ⁱ Vendor A wished to keep its name confidential. For consistency in our tables we are labeling the second vendor, UOP, as Vendor B.

operating and capital costs for a two-stage revamp, which is operated at a higher pressure.^j Thus, this vendor would recommend the use of a two stage unit right away instead of opting for other subunits at the higher diesel fuel sulfur levels. The other vendor, which we will call Vendor B, chose to estimate the operating and capital costs for a single stage revamp for moderate levels of desulfurization, which included a larger reactor, hydrogen purification, a recycle gas scrubber, and a color reactor to address the implications of increased reactor temperature. Then, to desulfurize diesel fuel to under 10 ppm, Vendor B would recommend a two stage unit, but without hydrogen purification and at lower temperature which negates the need to install a color reactor. While there are substantial hardware differences between the two vendors for desulfurizing diesel down to levels above 10 ppm, the differences between the vendors diminishes with deeper desulfurization as both vendors use a two stage approach. We believe that there are merits of using either approach and that both approaches would be used by different refiners. Thus, we based our rule on the cost of both vendors representing both approaches and we averaged them together. The technical approach generally used by each vendor to achieve reduced diesel fuel sulfur levels is summarized in the following table. The vendors assumed that the existing desulfurization unit in place would provide a number of hydrotreater subunits which would save on both capital and operating costs for a one or two stage revamp compared to whole new grassroots unit. These subunits include heat exchangers, a heater, a reactor filled with catalyst, two or more vessels used for separating hydrogen and any light ends produced by cracking during the desulfurization process, a compressor, and sometimes a scrubber. The desulfurization subunits listed here are discussed in detail in the feasibility section contained in Chapter IV.

^j Vendor A provided cost inputs for both low pressure and intermediate pressure units to NPC. The diesel desulfurization costs were similar for each, which suggests that one approach does not have a predictable advantage over the other, however, refinery configuration may provide an advantage of one approach over the other for each individual refiner.

Table V.C-3. Technology Projected to be Used to Achieve Various Diesel Fuel Sulfur Levels

Average Diesel Fuel Sulfur Level	<i>Vendor A</i>	<i>Vendor B</i>
30 ppm	Change to a more active catalyst Install recycle gas scrubber Modify compressor Install a second reactor, high pressure (900 psi) Use existing hot oil separator for interstage stripper	Change to a more active catalyst Install a recycle gas scrubber Purify make-up hydrogen Install a second reactor (650 psi) Increase temperature in the second reactor and install a color reactor
10 ppm	Same as above Use more catalyst Increase the size of the second reactor	Same as above Use more catalyst Increase the size of the second reactor
<10 ppm	Same as above Increase catalyst volume further Use an even larger second reactor Raise temperature in the second reactor	Same as above, Install an interstage stripper, which negates the need to purify hydrogen and increase the reactor bed temperature Increase size of the second reactor Increase catalyst volume

Prior to presenting the vendor inputs which allowed us to estimate the cost of meeting the 15 ppm cap standard, we will first qualify the information in terms of its perceived accuracy of the actual cost of desulfurizing diesel fuel. We received several comments from refiners which assert that the vendor costs are optimistic and need to be adjusted higher to better assess the costs. While the vendors costs may be optimistic, we believe that there are a multitude of reasons why the cost estimates should be optimistic.

First, capital costs can be lower than what the vendors project. Many refiners have used reactors, compressors, and other vessels which can be employed in a new or revamped diesel hydrotreating unit. We do not know to what extent that additional hydrotreating capacity can be met by using used vessels, however, we believe that at least a portion of the capital costs can be offset by used equipment.

There are also operational changes which refiners can make to reduce the difficulty and the cost of desulfurizing highway diesel fuel. Based on the information which we received from vendors and as made apparent in our cost analysis which follows, refiners with LCO in their diesel fuel would need to hydrotreat their highway diesel pool more severely resulting in a higher cost to meet the cap standard. We believe that these refiners could potentially avoid some or much of this higher cost by pursuing two specific options. The first option which we believe these refiners would consider would be to shift LCO to distillate fuels which do not face such stringent sulfur control, such as off-highway diesel fuel and heating oil. When we analyze the refineries which blend LCO into their diesel fuel, we find that a number of them also produce a significant quantity of high sulfur distillate. The lenient sulfur limits which regulate heating oil and off-highway diesel provide ample room for blending in substantial amounts of LCO. Because of the low cetane value inherent with LCO, refiners cannot simply dump a large amount into off-highway diesel since off-highway diesel must meet an ASTM cetane specification. Thus, we believe that refiners could distill its LCO into a light and heavy fraction and only shift the heavy fraction to off-highway diesel fuels. Essentially all of the sterically hindered compounds distill above 630 °F, so if refiners undercut their LCO to omit these compounds, they would cut out about 30 percent of their LCO. We expect that refiners could shift the same volume of non-LCO distillate from the highway distillate pool to the highway pool to maintain current production volumes of all fuels. In addition to the cetane limit which limits blending of LCO into off-highway diesel, the T-90 maximum established by ASTM limits would limit the amount of LCO, and especially heavy LCO, which can be moved from highway diesel fuel into the high sulfur distillate streams. For those refineries which could trade the heavy portion of LCO with other blendstocks in the high sulfur pool from own refinery or other refineries, we presume that those refiners could make that separations cheaply by using a splitting column for separating the undercut LCO from the uncracked heavy gasoil in the FCC bottoms.

Another option for refineries which are faced with treating LCO in its highway diesel fuel would be to sell off or trade their heavy LCO to refineries with a distillate hydrocracker. This is a viable option only for those refineries which are located close to another refinery with a distillate hydrocracker. The refinery with the distillate hydrocracker would upgrade the purchased LCO into gasoline or high quality diesel fuel. To allow this option, there must be a way to transfer the heavy LCO from the refinery with the unwanted LCO to the refinery with the hydrocracker, such as a pipeline or some form of water transport. We asked a refinery consultant to review this option. The refinery consultant corroborated the idea, but commented that trading the of blendstocks between refineries is a complicated business matter which is not practiced much outside the Gulf Coast, and that the refineries with hydrocrackers that would buy up and process this low quality LCO may have to modify their distillate hydrocrackers.⁴⁵ The modification which may be needed would be due to the more exothermic reaction temperature of treating LCO which could require refiners to install additional quenching in those hydrocrackers. Additionally, LCO can demand 60 to 80 percent more hydrogen for processing than straight run material. The refineries which can take advantage of selling or trading their LCO to these other

refineries are mostly located in the Gulf Coast where a significant number of refineries have hydrocrackers and such trading of blendstocks is commonplace. However, we also identified other refineries outside the Gulf Coast which could take advantage of their very close location to another refinery with a distillate hydrocracker. Through a quick analysis, we identified that these refineries which could sell off or trade their heavy LCO to other refineries with hydrocrackers produce about 25 percent of the highway diesel fuel in this country.

As we summarized in Chapter IV, catalysts are improving and expected to continue to improve. Our costs are based on vendor submissions and incorporate the most recent catalysts which they have to offer, however, as catalysts continue to improve, the cost of desulfurizing diesel fuel will continue to decrease.

Emerging technologies provide another opportunity for the cost of desulfurizing diesel fuel to be much lower than what we have estimated. Enchira Biosystems Corp., which was Energy BioSystems Corp., created and has been developing a process which uses genetically enhanced bacteria for oxidizing the sulfur molecules in diesel fuel, and then extracts the oxidized sulfur-containing petroleum molecules to sell as a surfactant on the chemicals market.⁴⁶ Another similar process has been created by Petrostar. The Petrostar process also oxidizes the sulfur molecules in diesel fuel, but uses an oxidation compound to do so.⁴⁷ Finally, Phillips has adapted their gasoline desulfurization process, which relies on adsorption, to diesel fuel. These various processes are still being developed, though, and may not be ready in time for making the implementation date of this final rule.

In summary, if the vendor cost estimates are optimistically low, there are a number of reasons why the cost of desulfurizing highway diesel fuel to meet the 15 ppm cap standard are likely to be low. Vendors are expected to continue to improve their desulfurization technology such as the activity of their catalysts. Also, refiners have several cost cutting options at their disposal such as using existing spare equipment to lower their capital costs. Also, refiners may be able to resort to either of two operational options to reduce the amount of LCO in their highway diesel fuel. Furthermore, refiners could choose to use emerging technology which could offer significant reductions in the cost of desulfurizing diesel fuel.

We next present diesel fuel desulfurization information provided by the vendors for typical diesel fuel blends containing 8 percent and 10 percent coker, 23 percent and 25 percent LCO and the balance straight run, and another containing only straight run. This information is summarized below in Tables V.C-4 & 5. This information was provided either for a revamp or for a grassroots unit, which is indicated.

**Table V.C-4. Process Projections to Desulfurize a Typical Diesel Fuel^A
(Information Provided for a Retrofit Unless Indicated)**

	<i>Vendor A 50 ppm 900 psi Hydrotreat.</i>	<i>Vendor A 10 ppm 900 psi Hydrotreat.</i>	<i>Vendor A 7 ppm 900 psi Hydrotreat.</i>	<i>Vendor B 30 ppm 650 psi Hydrotreat.</i>	<i>Vendor B 10 ppm 650 psi Hydrotreat.</i>	<i>Vendor B 7 ppm 650 psi Hydrotreat.</i>
Capacity (bbl/stream day)	25,000	25,000	25,000	31,200	31,200	31,200
Capital Cost (ISBL) (MM\$)	15 - 18	15 - 18	1 more than at 10 ppm	5.5	7	15
LHSV (Liquid Hour Space Velocity (Hr ⁻¹))	2.5 1.25*	1.5 1.0*	0.8 ^B	1.5	0.9	NP
Chemical Hydrogen Consumption (SCF/bbl)	100 325 ^B	160 375 ^B	20 more than at 10 ppm	70 330 ^B	115 375 ^B	NP
Electricity (KwH/bbl)	0.30	0.36	NP	0.5	0.6	NP
HP Steam (Lb/bbl)	-	-	-	-	-	-
Fuel Gas (BTU/bbl)	-2.2 ^C	-2.9	NP	100	100	NP
Catalyst Cost (\$/bbl)	0.06	0.08	NP	0.14	0.41	NP
Yield Loss (wt%) Diesel	1.42 ^B	1.51 ^B	NP	NP	NP	NP
Naphtha	-0.89 ^B	-1.06 ^B	NP	NP	NP	NP
LPG	-0.05 ^B	-0.06 ^B	NP	NP	NP	NP
Fuel Gas	-0.09 ^B	-0.10 ^B	NP	NP	NP	NP

^A This diesel fuel contains 23% LCO, 8% coker, and 69% straight run for Vendor A, and 25% LCO, 10% coker and 65% straight run for Vendor B.

Sulfur levels in the table are averages.

NP = not provided.

^B Information provided for a grassroots unit.

^C Information provided for achieving 30 ppm; negative values indicate exothermic reactions.

**Table V.C-5. Process Projections to Desulfurize 100% Straight Run Diesel Fuel
(Information is for a Grassroots Unit)**

	<i>Vendor A 50 ppm 800 psi Hydrotreating</i>	<i>Vendor A 10 ppm 800 psi Hydrotreating</i>
Capacity BPSD (bbl/day)	25,000	25,000
Capital Cost (ISBL) (MMS)	NP	NP
LHSV (Liquid Hour Space Velocity (Hr ⁻¹))	1.6	1.25
Hydrogen Consumption (SCF/bbl)	210	225
Electricity (KwH/bbl)	NP	NP
HP Steam (Lb/bbl)	-	-
Fuel Gas (BTU/bbl)	NP	NP
Catalyst Cost (\$/BPSD)	34	45
Yield Loss (wt%) Diesel Naphtha LPG Fuel Gas	NP	NP

NP = not provided.

Sulfur levels in the table are averages.

We are aware that there are potentially other capital and operating costs in the refinery which would contribute the projected cost of desulfurizing diesel fuel beyond that provided to us by the vendors. For example, refiners may need to expand their amine plant or their sulfur plant to enable the processing of the sulfur compounds removed from diesel fuel. Then the small amount of additional sulfur compounds treated would incur additional operating costs. Thus, we adjusted the projected capital and operating costs upward to account for these other potential costs which we have not accounted for directly. Our contingency factors, described further below, are 1.18 for capital and 1.12 for operating costs.

d. Development of Diesel Desulfurization Cost Projections

After obtaining the information from Vendors A and B, and corroborating their submissions based on some other information which we obtained from other vendors, we needed to apply this information to estimate the cost of meeting the 15 ppm highway diesel fuel cost standard. However, in many cases the information provided by the vendors was not sufficient for inserting directly into our cost model. Vendors A and B provided most of the information needed to cost out both a revamp and a grassroots unit. However, for some of the cost inputs for our refinery model, the information provided by the vendors is for a grassroots unit and it must be adjusted to reflect the impact or cost of a revamp, and vice versa. In other cases, no information was presented at all so we developed a method for estimating the necessary cost inputs.

In the case where we only received information for a grassroots unit for a specific cost, we typically estimated the cost of a revamp using ratios of the liquid hour space velocity (LHSV) provided by the vendor for a revamp. Using LHSV seems reasonable considering that the value is inversely proportional to the catalyst and reactor volume projected to be necessary to accomplish the required desulfurization. Thus, applying the inverse of LHSV for meeting differing sulfur levels should be a good surrogate for the ratio of costs. We did not receive information from Vendor B for desulfurizing 100% straight run diesel fuel, but instead of relying only on the information from Vendor A, we projected Vendor B's costs using the percentage difference in costs estimated by Vendor A for treating a 100% straight run feed compared to a typical feed. Using information from both vendors for estimating the cost for the sensitivity analysis results in a better comparison with the case which assumed a typical mix of diesel blendstocks. For meeting the 15 ppm cap standard, which we estimate to mean achieving 7 ppm on average, the vendors did not provide specific cost information for many of the individual cost elements, thus we extrapolated the costs. While hydrogen consumption and space velocity information was provided by Vendor A specifically, the other cost elements, such as catalyst cost, yield loss and utility costs were projected using the ratio of the LHSV or by extrapolating the costs from the higher sulfur levels. These extrapolations are described in detail below Tables V.C-6 and V.C-7.

Cost Projections for a Typical Feed

The adjusted vendor capital and operating cost information is summarized in Tables V.C-6. and V.C-7. below.

Table V.C-6. Process Projections for Revamping an Existing Highway Diesel Hydrotreater for Further Desulfurizing a Typical Diesel Fuel^A

	<i>900 psi (Based on Vendor A)</i>			<i>650 psi (Based on Vendor B)</i>		
Average Sulfur Level	<i>50 ppm</i>	<i>10 ppm</i>	<i>7 ppm</i>	<i>30 ppm</i>	<i>10 ppm</i>	<i>7 ppm</i>
Capacity (bbl/stream day)	25,000	25,000	25,000	31,200	31,200	31,200
Capital Cost (ISBL) (MM\$)	16	18	19	5.5	7	15
LHSV (Liquid Hour Space Velocity (Hr ⁻¹))	2.5	1.5	1.2	1.5	0.9	0.7
Hydrogen Consumption (SCF/bbl)	125	185	205	95	154	160
Electricity (KwH/bbl)	0.24	0.36	0.37	0.5	0.6	0.6
Fuel Gas (BTU/bbl)	-1.5	-2.9	-3.0	100	100	100
Catalyst Cost (\$/bbl)	0.06	0.08	0.1	0.14	0.41	0.51
Yield Loss (%)						
Diesel	0.8	1.0	1.3	0.9	1.0	1.3
Naphtha	-0.5	-0.71	-0.88	-0.54	-0.71	-0.88
LPG	-0.03	-0.04	-0.05	-0.03	-0.04	-0.05
Fuel Gas	-0.05	-0.07	-0.08	-0.05	-0.07	-0.08

^A This typical diesel fuel contains 23% LCO, 8% coker, and 69% straight run for Vendor A, and 25% LCO, 10% coker and 65% straight run for Vendor B.

When available, the information contained in Table V.D-6. reflects exactly the information provided by the two vendors. However, the vendors did not provide projections for some of the relevant factors. These factors were estimated from the information provided by the other vendor or otherwise, as described below.

As stated above under Table V.C-4., Vendor A provided a range of \$15 - \$18 million for the capital costs of desulfurizing diesel fuel from the base to 50 ppm and from the base down to 10 ppm. Consistent with the methodology laid out above, we assigned the capital cost of desulfurizing diesel fuel with 23 percent LCO down to 50 ppm as \$16 million, and the cost of producing 10 ppm diesel as \$18 million. For achieving a sulfur level of 5 ppm, Vendor A estimated the additional capital cost to be \$1 million more, which we used for our estimated 7 ppm case. For Vendor B, we have two sources of information for the capital costs which seem to vary at the 10 ppm level. We based the cost analysis on the explicit cost provided by Vendor B. However, interpolating the capital cost from Vendor B's second information source suggests that the capital cost for desulfurizing diesel fuel to the 10 ppm level may be fifty percent higher.

We are aware that small leaks in the heat exchangers of existing highway diesel hydrotreating unit can lead to contamination of the product stream. Even a small leak of tenths of a percent in volume of high sulfur feed into the very low sulfur product could ruin batches of the product. For this reason, many refiners who chose to revamp their existing diesel hydrotreaters are expected to take preventative measures against contamination by welding the heat exchanger tubes to the plates, or by replacing their heat exchangers altogether.⁴⁸ To account for this added cost we assumed that each refinery would invest a million dollars to revamp or, in some cases, completely replace their highway diesel heat exchangers to ensure that they could meet a 15 ppm diesel fuel sulfur standard.⁴⁹

Since neither Vendor A nor Vendor B provided estimates of the LHSV for a retrofit unit down to 5 ppm, we calculated Vendor A's ratio of the LHSV for achieving 5 ppm to the LHSV for achieving 10 ppm for a grassroot unit, and applied the ratio to the LHSV values for retrofits for both Vendor A and Vendor B for 10 ppm.

Vendor A estimated hydrogen consumption for achieving 5 ppm as 25 SCF/bbl higher than that for achieving 10 ppm. To desulfurize down to 7 ppm from 10 ppm, we assume that an additional 20 scf/bbl would be necessary. Since Vendor B did not provide a estimate for achieving 7 ppm, we applied Vendor A's increased hydrogen consumption to Vendor B. At all levels of desulfurization, we assume that each characteristic refinery would lose 25 standard cubic feet per barrel (SCF/bbl) hydrogen due to solution and purge losses for the revamp.^{50 51} Solution losses of hydrogen is the hydrogen which becomes entrained in the highway diesel fuel and thus is no longer available to recycle back to the diesel hydrotreater. Purge losses is the intentional bleeding off of the hydrogen stream and sending that stream to plant gas to prevent a

high concentration of nonreactive gases, such as methane, from being recycled back to the reactors.

The electricity necessary for achieving 7 ppm sulfur is extrapolated from the 10 ppm and 50 ppm cases for both Vendor A and Vendor B.

The catalyst cost for achieving 7 ppm for a revamp for Vendor A and Vendor B is estimated by multiplying Vendor A's ratio of the LHSV for 10 ppm divided by the LHSV for 7 ppm for a grassroots unit times the LHSV for 10 ppm for a revamp.

The yield loss and resulting by products produced which was provided by Vendor A for a grassroots unit was adjusted to project the yield loss for a revamped unit using the ratio of the LHSV of a grassroots unit to the LHSV of a retrofitted unit. Since Vendor B did not provide yield loss information, Vendor A's yield loss and by-product information was applied to Vendor B. This seems reasonable because the LHSV (which indicates the contact time which diesel has with the catalyst) for both vendors is similar and yield loss would likely be proportional to the contact time of diesel fuel with the catalyst.

*Cost Projections for a Straight Run Feed***Table V.C-7. Process Projections for Revamping an Existing Highway Diesel Hydrotreater for Desulfurizing 100% Straight Run Diesel Fuel**

	<i>800 psi (Based on Vendor A)</i>			<i>650 psi (Based on Vendor B but adjusted using Vendor A's information)</i>		
	<i>50 ppm</i>	<i>10 ppm</i>	<i>7 ppm</i>	<i>30 ppm</i>	<i>10 ppm</i>	<i>7 ppm</i>
Capacity (bbl/stream day)	25,000	25,000	25,000	31,200	31,200	31,200
Capital Cost (ISBL) (MMS)	15	17	18	5.5	6.2	11
LHSV Liquid Hour Space Velocity (Hr ⁻¹)	2.8	1.9	1.5	1.7	1.1	0.9
Hydrogen Consumption (SCF/bbl)	95	100	107	80	84	90
Electricity (KwH/bbl)	0.28	0.35	0.35	0.5	0.6	0.6
Fuel Gas (BTU/bbl)	-1.5	-2.9	-3.0	100	100	100
Catalyst Cost (\$/bbl)	0.03	0.05	0.07	0.11	0.33	0.41
Yield Loss (wt%) Diesel	0.6	0.8	1.0	0.7	0.8	1.0
Naphtha	-0.4	-0.6	-0.7	-0.4	-0.6	-0.7
LPG	-0.02	-0.03	-0.04	-0.03	-0.03	-0.04
Fuel Gas	-0.04	-0.05	-0.07	-0.04	-0.05	-0.07

When available, the information contained in Table V.C-7. reflects exactly the information provided by the two vendors. However, the vendors did not provide projections for some of the relevant factors. These factors were estimated from the information provided by the other vendor or otherwise, as described below.

Vendor A did not provide a specific capital cost for a 100 percent straight run diesel case. Instead, the vendor estimated a capital cost of \$15-18 million for a refinery processing different amounts of LCO to meet a range of final sulfur levels of 10-50 ppm. Based on discussions with

the vendors, we surmised that increased amounts of LCO provides a similar extent of difficulty for desulfurization as decreasing the sulfur level in this range of desulfurization. Thus, we estimated the capital cost for the 100 percent straight run case for 50 ppm sulfur to be at the lowest end of the range (\$15 million) and to be \$16 million for 10 ppm, since diesel fuel without LCO is easier to desulfurize than diesel containing LCO. Also, the increment of \$1 million was the cost estimated by this vendor of reducing sulfur from 10 ppm to 5-10 ppm for LCO containing material, so we used the same increment for this case as well. In Table V.C-6. above, the capital cost for treating a typical diesel fuel falls within the upper part of Vendor A's capital cost range.

Vendor B also did not provide capital costs for a no LCO case. Since we had no information from Vendor B for how it would allocate its capital costs for varying levels of LCO, we assumed that the capital costs for the no LCO cases producing sulfur at 10 ppm or higher would be the same as those for the 23 percent LCO case. While this assumption may be conservative, we felt comfortable with this assumption because of the low capital costs projected by Vendor B. However, below 10 ppm, instead of the large increase in capital cost projected for the 23 percent LCO case, we projected that the capital cost would be halfway between the increase for the 23 percent case, which would be \$11 million. This assumption seemed reasonable since straight run contains some sterically hindered compounds which requires more reactor volume to treat, although still much less than that of the 23 percent LCO case.

The hydrogen consumption for this retrofit case was calculated using the ratios of the retrofit case for the case with 23 percent LCO. Vendor B's hydrogen consumption for a grassroots case with no LCO was estimated first assuming the same hydrogen consumption as Vendor A, however, the retrofit hydrogen consumption for Vendor B is a smaller ratio than that of Vendor A.

The LHSV for both vendors' retrofit technology for the no LCO case was estimated from the information which they provided for the grassroots units. The ratio of the LHSV for the grassroots units treating no LCO to the LHSV for the grassroots unit treating 23 percent LCO was applied to the LHSV for the retrofit unit treating 23 percent LCO to project the LHSV for the retrofit unit treating no LCO.

Electricity consumption for the no LCO cases was assumed to be 97 percent of that for the 23 percent LCO cases based on the ratio of specific gravities for the two different feeds, since the density of the fuel governs the pumping energy consumed for moving the fuel. Fuel gas consumption for treating the non-LCO feed was assumed to be the same as that for the 23 percent LCO case. The catalyst cost for the non-LCO feed was assumed to be proportional to the ratio of the LHSV of the no LCO and 23 percent LCO cases. The yield loss of the no LCO case was adjusted downward from the 23 percent LCO case using ratios of the LHSV; since Vendor B did

not provide yield loss information, Vendor A's information was applied to Vendor B's technology as well.

e. Development of Desulfurization Cost Factors for Individual Diesel Blendstocks

Once we established the inputs for estimating the cost of desulfurizing a typical diesel fuel containing both straight run and cracked stocks, we set out to estimate the inputs for each individual blendstock. Configuring our cost analysis to estimate costs based on the estimated highway diesel blend of each refinery gave us more confidence in our cost analysis. We already had the inputs for straight run from a submission from Vendor A. Next we needed to estimate the inputs for light cycle oil and for the other cracked stocks. We used some of the information we obtained from our discussions with the vendors to make these estimates. Since we need to estimate costs for both a revamp and a grassroots units for each refinery, it was necessary to develop costs for both. These costs are presented in Table V.C-8 for a revamped unit, and further below in Table V.C-9 for a grassroots unit. The methodology for developing those costs are described below each Table.

Individual Blendstock Process Projections for a Revamp

These process projections are for revamping an existing desulfurization unit with additional hardware enabling the combined older and new unit to meet the 15 ppm sulfur cap standard. If a refiner decides to replace their existing highway diesel fuel desulfurization unit with a new grassroots unit, we assume that the operating costs of the new unit would still be the same as a revamped unit because the refiner has already been incurring the operating cost for producing 350 ppm highway diesel fuel. We assume the refiner would, however, incur all the capital cost of the new unit.

Table V.C-8. Process Projections for Revamping an Existing Highway Diesel Hydrotreater for Further Desulfurizing Diesel Fuel Blendstocks to Meet a 15 ppm Cap Standard

	<i>Straight Run</i>	<i>Other Cracked Stocks</i>	<i>Light Cycle Oil</i>
Capacity BPSD (bbl/day)	25,000	25,000	25,000
Capital Cost (ISBL) (MMS)	16	19	22
LHSV (Liquid Hour Space Velocity (Hr ⁻¹))	1.25	0.7	0.6
Hydrogen Consumption (SCF/bbl)	96	230	375
Electricity (KwH/bbl)	0.4	0.7	0.8
HP Steam (Lb/bbl)	-	-	-
Fuel Gas (BTU/bbl)	40	70	80
Catalyst Cost (\$/BPSD)	0.2	0.4	0.5
Yield Loss (wt%) Diesel	1.0	1.9	2.2
Naphtha	-0.7	-1.3	-1.5
LPG	-0.04	-0.07	-0.08
Fuel Gas	-0.04	-0.11	-0.13

The information in Table V.C-8 was derived from the Tables V.C-4-7 above, from Table V.C-9 below, and using other inputs and assumptions as described below.

Capital Costs

The inside battery limits (ISBL) capital costs for revamping a hydrotreater to handle straight run was estimated by averaging the values for Vendors A and B from Table V.D-7. A \$1 million sum was added to that sum to account for improvements to existing heat exchangers such as welding the tubes to the tubesheets, and for some refiners to replace their heat exchangers altogether.

The ISBL capital cost of treating coker and other cracked stocks is based on the need to have more catalyst and reactor volume and probably a higher pressure than straight run to treat a greater volume of sterically hindered compounds. The difficulty in treating coker distillate was presumed to be similar to treating 1/3 LCO, 1/3 coker distillate and 1/3 straight run, because the volume of sterically hindered compounds is similar to that combination of blendstocks. This is a useful comparison to make because in their submission to us, Vendor A provided a capital cost estimate for treating such a mix down to 10 ppm. Vendor A presumed that refiners would need to invest \$19 million, which is at the high end of the range given by Vendor A for achieving 10 ppm for a range of feeds, of which this particular blend of diesel stocks was the worst. This value was increased by \$1 million to achieve 7 ppm and another \$1 million to revamp or replace the heat exchangers, which increased the sum to \$21 million. Like the case with 23 percent LCO in the diesel fuel, Vendor B's capital costs were presumed to be \$4 million less than Vendor A's capital costs, which would still include the \$1 million for improvements to existing heat exchangers. On average, treating coker distillate is estimated to cost \$19 in capital costs.

The ISBL capital cost for a revamp to an existing diesel hydrotreater for treating LCO can be estimated from some assumptions on the relative difficulty of treating the sterically hindered compounds contained in LCO. LCO contains proportionally more sterically hindered compounds than what the other cracked stocks are estimated to contain relative to straight run (coker distillate contains slightly more than twice the percentage of sterically hindered compounds as straight run, and LCO contains a little more than twice the percentage of sterically hindered compounds as the other cracked streams).⁵² Based on this observation and assuming that the increased reactor volume and higher pressure needed to treat LCO is proportionally higher than treating other cracked stocks compared to straight run distillate, we presume that the capital costs are proportionally higher as well. Thus, the capital cost was increased by the same amount over the other cracked stocks as the difference between the other cracked stocks and straight run, which is \$3 million more. Then the same \$1 million increase was assumed for improving the heat exchangers. Thus, hydrotreating LCO is estimated to cost \$22 million in capital costs.

Hydrogen Consumption

The hydrogen consumption for treating straight run, other cracked stocks and LCO was calculated from the values in Table V.C-8 for desulfurizing these untreated distillate streams in a grassroots hydrotreating unit down to 7 ppm. Based on the relative hydrogen consumption for revamped units versus grassroots units from Vendor A and B for a typical feed, the revamped hydrogen consumption is estimated to be about one-third of the hydrogen consumption of the grassroots unit for straight run and LCO. However, because of the high olefin content of the other cracked stocks which consumes a significant amount of hydrogen in a first stage, a revamp would only be expected to require one-fourth of the estimated amount of hydrogen consumed in a grassroots unit. These factors are applied to the hydrogen consumption values without losses,

and the losses are added back after multiplication by the various factors. For treating straight run and other cracked stocks, the losses for a grassroots unit are small and assumed to not be lower for a revamped unit. However, the larger losses for treating LCO are assumed to decrease to 25 scf/bbl from the 50 scf/bbl assumed for the grassroots unit. Based on these factors, hydrogen consumption, including losses, for a revamped highway diesel desulfurization unit for meeting the 15 ppm cap standard is 96 scf/bbl for straight run, 230 scf/bbl for other cracked stocks, and 375 scf/bbl for LCO

Space Velocity and Other Operating Costs

The estimated space velocity for a revamped unit treating straight run, other cracked stocks and LCO was calculated from the space velocity values for a grassroots unit summarized below. According to Vendor A, who estimated the space velocity for both a grassroots unit and a revamp for desulfurizing an average blend of diesel fuel down to an average of 10 ppm, a revamped unit's space velocity is 50 percent higher than a grassroots unit. This factor was applied to the space velocities for a grassroots unit listed in Table V.C-8.

The utilities, the catalyst cost and the yield loss were costed out using the space velocity as the cost factor. This calculation was implemented by using the reciprocal of the space velocity, which is the residence time, and multiplying it times each of these operating cost inputs. The catalyst volume would correlate exactly with this relationship, and a less than perfect, but reasonable, correlation would be expected with yield loss and utility cost. The loss of diesel mass was estimated with this approach, however, the cost was ultimately calculated outside of these equations as described below.

Individual Blendstock Process Projections for a Grassroots Unit

Similar process projections are provided for a grassroots unit in this section. It is important to note that a refinery only producing, or predominantly producing, non-highway diesel fuel would be faced with these estimated costs. However, as stated above, if a refinery has an existing hydrotreater for desulfurizing their highway diesel fuel and they install a grassroots unit instead of revamping their existing hydrotreater, they would incur the capital costs outlined here, but their operating costs would be based on a revamp as described above.

Table V.C-9. Process Projections for Installing a New Grassroots Unit for Desulfurizing Untreated Diesel Fuel Blendstocks to Meet a 15 ppm Cap Standard

	<i>Straight Run</i>	<i>Coker Distillate</i>	<i>Light Cycle Oil</i>
Capacity BPSD (bbl/day)	25,000	25,000	25,000
Capital Cost (ISBL) (MM\$)	31	37	42
LHSV (Liquid Hour Space Velocity (Hr ⁻¹))	0.8	0.5	0.4
Hydrogen Consumption (SCF/bbl)	240	850	1100
Electricity (KwH/bbl)	0.6	1.1	1.2
HP Steam (Lb/bbl)	-	-	-
Fuel Gas (BTU/bbl)	60	105	120
Catalyst Cost (\$/BPSD)	0.3	0.6	0.8
Yield Loss (%) Diesel	1.5	2.9	3.3
Naphtha	1.1	2.0	2.3
LPG	0.06	0.11	0.12
Fuel Gas	0.06	0.17	0.20

The information in Table V.C-9 was derived from Tables V.C-4 through Table V.C-7 above for desulfurizing highway diesel fuel down to 7 ppm, and using other inputs and assumptions as described here.

Capital Costs

The capital costs for a grassroots hydrotreater was calculated simply by increasing the cost of a revamp by a factor two. This same calculation was used for straight run, coker distillate and light cycle oil. The basis for this calculation is that Vendor A's information provided for both a revamp and a grassroots unit for desulfurizing a typical feed to meet a stringent sulfur standard showed that the grassroots unit's ISBL investment cost is projected to cost two times higher than a revamp. The \$1 million sum which was added to the revamped case to account for

improvements to existing heat exchangers was not included in the grassroots capital cost since the grassroots unit includes new heat exchangers.

Hydrogen Consumption

The hydrogen consumption rate for straight run, coker distillate and light cycle oil were estimated by applying certain factors used by vendors for estimating hydrogen consumption. One such factor is that about 25 standard cubic feet per barrel (scf/bbl) of hydrogen is consumed for each volume percent of polynuclear aromatics saturated to monoaromatics.^{53 54} As described in Chapter IV, many of the polynuclear aromatics (PNAs) are saturated to monoaromatics to enable desulfurization of the sterically hindered sulfur compounds. On a molecular level, four hydrogen atoms are consumed for each PNA saturated to a monoaromatic. According to Mathpro, about half the total amount of aromatics in a diesel blend are PNAs: straight run contains about 8 volume percent PNAs, coker distillate contains about 20 volume percent PNAs, and LCO contains about 55 volume percent PNAs.⁵⁵ However, these values are typical values within a range of values which can vary depending on the type of crude oil processed by each refinery and operating conditions of the unit producing the individual blendstock. Since we do not know these variables for each refinery producing highway diesel fuel, we used the typical values listed here. In a submission from Vendor A, which was based on feed qualities from Mathpro, 5 volume percent of the PNAs are estimated to be saturated to monoaromatics to achieve an average of 10 ppm sulfur. The conversion of this 5 volume percent represents about two thirds of the total volume of PNAs shown to be typical for straight run by Mathpro. Thus, if a similar fraction of PNAs are saturated for each blendstock, 12 percent of the PNAs in coker (2/3 of 20) and 34 percent of the PNAs in LCO (2/3 of 55) would be converted to monoaromatics. Since we don't have other information on which we can base our estimate of the hydrogen consumption for the saturation of PNAs in LCO and other cracked stocks, we used this factor for estimating this form of hydrogen consumption. As an example of how to apply the factor described above, to estimate the hydrogen consumed due to the saturation of PNAs when desulfurizing straight run down from uncontrolled levels of sulfur to 10 ppm, we would multiply the 25 scf/bbl factor times the 5 volume percent of PNAs saturated, thus, 125 scf/bbl of hydrogen would be consumed.

Of course the sulfur in each of these different blendstocks must be hydrotreated out of the sulfur-containing hydrocarbon compounds. For most of the sulfur, four hydrogen atoms are consumed to remove each sulfur atom. According to Vendor B, removing sulfur from diesel fuel consumes 125 scf/bbl for each weight percent of sulfur removed.⁵⁶ According to Mathpro, typical straight run, LCO, and coker distillate contain on the order of 0.7, 1.3 and 3 percent sulfur, respectively. As an example, removing the sulfur from a typical straight run feedstock would consume 85 scf/bbl of hydrogen (0.7 multiplied times 125 scf/bbl) to desulfurize each barrel of untreated straight run diesel fuel down to 10 ppm sulfur.

During the hydrotreating process, the hydrocarbons which are olefins are very readily and completely saturated to paraffins which consumes two additional atoms of hydrogen for each olefin. Coker distillate, and to a lesser degree, LCO contain some olefins which are readily saturated at the top of any hydrotreater. One vendor we spoke to estimated that coker distillate contain 30 volume percent olefins, which consumes on the order of 6 scf/bbl of hydrogen per each volume percent of olefins saturated.⁵⁷ We do not have an estimate for the olefin content of LCO, however, we believe that LCO does contain some so we presume that it is about one-fifth as much as coker distillate, or about 6 volume percent. As an example, saturating the olefins in coker would consume 180 scf/bbl of hydrogen (30 times 6 scf/bbl) per each barrel of coker distillate hydrotreated

Since the level of conversion of polyaromatics to monoaromatics was consistent with achieving 10 ppm sulfur, this value must be increased to be consistent with achieving 7 ppm sulfur. According to Vendor A, about another 20 scf/bbl are consumed to make up the difference between 7 ppm and 10 ppm for a typical feed which, as described above, is comprised of 69 percent straight run, 8 percent coker and 23 percent LCO. Allocating this increased hydrogen consumption to each blendstock we estimate that straight run will consume 8 scf/bbl more hydrogen, other cracked stocks would consume about 15 scf/bbl more hydrogen and LCO would consume about 50 scf/bbl more hydrogen. This allocation is based on the relative concentrations of PNAs contained in each of these blendstocks.

The estimated amount of hydrogen consumption for each blendstock is summarized in the following table.

Table V.C-10. Estimated Hydrogen Consumption to Desulfurize Nontreated Distillate, Stocks to Meet the 15 ppm Highway Diesel Fuel Sulfur Cap

	<i>Conversion of Polynuclear Aromatics to Monoaromatics</i>	<i>Sulfur Removal</i>	<i>Saturation of Olefins</i>	<i>Total Hydrogen Consumption</i>
Straight Run	133	85	0	223
Other Cracked Stocks	325	375	180	875
LCO	900	165	35	1100

After deriving these hydrogen consumption estimates for each blendstock, we compared these estimates to the estimated amount of hydrogen consumed by Vendors A and B for

desulfurizing three different feeds down to 10 ppm. Vendor A provided hydrogen consumption estimates for straight run, a blend of 69 percent straight run, 8 percent coker and 23 percent LCO, and a blend of 1/3 straight run, 1/3 coker, and 1/3 LCO (not summarized above, but was submitted to the docket). Vendor B provided hydrogen consumption estimates for a blend of 65 percent straight run, 10 percent coker and 25 percent LCO. This comparison is summarized in Table V.C-11 below.

As shown in Table V.C-11, our estimated hydrogen consumption values seem to agree fairly well with those provided by the vendors. The straight run and 1/3-1/3-1/3 feedstock are both quite close. However, the estimated hydrogen consumption for a typical feed, which is either 69 or 65 percent SR, 8 or 10 percent coker, and 23 or 25 percent LCO is between 20 to 30 percent high, with the highest discrepancy with Vendor B's estimated hydrogen demand. This 69 or 65 percent SR feed is probably the most important since it really represents the average of diesel fuel today. The 1/3 SR, 1/3 other cracked and 1/3 LCO, stock feed is heavier than average diesel fuel today. Because we are only modelling the average endpoint, we would be expected to estimate a lower hydrogen consumption value compared to heavier feeds. For these reasons, we recalculated the hydrogen consumption adjusting it downward by 5 percent. These recalculated values are summarized in the last column in Table V.C-11. This recalculation reduces the estimated hydrogen consumption values of straight run from 223 to 213 scf/bbl, other cracked stocks from 875 to 830 scf/bbl, and LCO from 1100 to 1045 scf/bbl.

Table V.C-11. Comparison of Calculated Hydrogen Consumption with the Hydrogen Consumption provided by Vendors A and B for Specific Distillate Feeds

	<i>Vendor A</i>	<i>Vendor B</i>	<i>Calculated Hydrogen Consumption</i>	<i>Recalculated Hydrogen Consumption</i>
Straight Run	233		223	212
69 % straight run, 8 % coker, 23% LCO	395		476	450
65 % SR, 8% coker, 23% LCO		395	507	480
1/3 straight run, 1/3 coker, and 1/3 LCO	730		732	695

The hydrogen consumption values summarized in Table V.C-11 are only meant to represent the chemical consumption of the hydrogen consumption, which is the hydrogen which reacts with the hydrocarbon. Additional hydrogen is lost through entrainment in the diesel fuel

and other losses. When hydrogen becomes entrained in the diesel fuel and it is not recovered for reuse, it is called solution losses. Other losses can occur through leaks from the unit or perhaps due to flaring in cases of unit overpressure or due to a constant purge to prevent accumulation of inerts in the hydrogen stream. To account for these losses, we added 25 scf/bbl for straight run and the other cracked stocks, and 50 scf/bbl for LCO. Accounting for hydrogen losses, our hydrogen consumption values increase to about 240 scf/bbl for straight run, 850 scf/bbl for other cracked stocks, and 1100 scf/bbl for LCO.

Space Velocity and Other Operating Costs

The space velocity for a grassroots hydrotreater was calculated by multiplying the space velocity of a revamp by a factor of 0.66 (a fifty percent increase in residence time). This same adjustment was used for straight run, coker distillate and light cycle oil. The information provided by Vendor A was the basis for using this adjustment factor as the space velocity for a grassroots diesel hydrotreater treating a typical blend of straight run, coker distillate and light cycle oil was two thirds the space velocity of a revamp. In terms of residence time, a grassroots unit requires about 50 percent more residence time compared to a unit which is a revamp to an existing diesel hydrotreater.

The utilities, the catalyst cost and the yield loss were costed out using the space velocity as the cost factor. This calculation was made by using the reciprocal of the space velocity, which is the residence time, and multiplying it times each of these operating cost inputs. The catalyst volume correlates exactly with this relationship, and a reasonable correlation would be expected with yield loss and utility cost as well. The loss of diesel mass was estimated with this approach, however, the cost was ultimately calculated outside of these equations as described below.

Hydrocrackate Processing and Tankage Costs

We believe that refineries with hydrocrackers will have to invest some capital and incur some operating costs to ensure that recombination reactions at the exit of the second stage of their hydrocracker does not cause the diesel fuel being produced by their hydrocracker to exceed the cap standard. The hydrocracker is a very severe hydrotreating unit capable of hydrotreating its product from thousands of ppm sulfur to essentially zero ppm sulfur, however, hydrogen sulfide recombination reactions which occur at the end of the cracking stage, and fluctuations in unit operations, such as temperature and catalyst life, can result in the hydrocracker diesel product having up to 30 ppm sulfur in its product stream.^{58 59} Thus, we assume that refiners will need to install a finishing reactor for the diesel stream produced by the hydrocracker. According to vendors, this finishing reactor is a low temperature, low pressure hydrotreater which can desulfurize the simple sulfur compounds which are formed in the cracking stage of the hydrocracker. The finishing reactor adds about 0.25 c/gal to the cost of desulfurizing diesel fuel for those typical refineries with distillate hydrocrackers.

Additionally, since the diesel sulfur standard is a cap standard, we are taking into account tankage costs that would be incurred due to the cap standard. We believe that refiners could store high sulfur batches of highway diesel fuel during a shutdown of the highway diesel hydrotreater. Highway diesel production would cease in the short term, but the rest of the refinery could remain operative. To account for this, we provided for the installation of a tank that would store 10 days of highway diesel production sufficient for a 10 day emergency turnaround which is typical for the industry, which would be about 3 million dollars for a 270,000 barrel storage tank.⁶⁰ This amount of storage should be adequate for most unanticipated turnarounds. We presumed that half of refiners would need to add such storage, the other half of refineries either already having such storage available, have the capability to send the untreated blendstock to a nearby refinery which had spare capacity for treating this high sulfur blendstock, or would downgrade the high sulfur highway diesel batch to the high sulfur diesel pool (there is already a significant amount of highway diesel fuel sold as off-highway diesel fuel).^k Adding such a storage tank to the typical refinery adds about 0.17 c/gal to the cost of desulfurizing diesel fuel for that refinery.

The cost inputs for the storage tank and the finishing reactor are summarized in Table V.C-12.

^k Presuming that half of refineries will add a storage tank is reasonable, because some refineries will not need to add a storage tank due to blendstock shifting and downgrading options to them, and that some will have to install such a tank since they will not have such options available to them.

Table V.C-12. Process Operations Information for Additional Units used in the Desulfurization Cost Analysis

	<i>Diesel Storage Tank</i>	<i>Distillate Hydrocracker Post Treat Reactor</i>
Capacity	50,000 bbls	25,000 (bbl/day)
Capital Cost (MM\$)	0.75	5.7 ⁶¹
Electricity (KwH/bbl)	---	0.98
HP Steam (Lb/bbl)	---	4.2
Fuel Gas (BTU/bbl)	---	18
Cooling Water (Gal/bbl)	---	5
Operating Cost (\$/bbl)	none*	---

* No operating costs are estimated directly, however both the ISBL to OSBL factor and the capital contingency factor used for desulfurization processes is used for the tankage as well, which we believe to be excessive for storage tanks so it is presumed to cover the operating cost.

Refiners will also likely invest in a diesel fuel sulfur analyzer.⁶² The availability of a sulfur analyzer at the refinery would provide essentially real-time information regarding the sulfur levels of important streams in the refinery and facilitate operational modifications to prevent excursions above the sulfur cap. Based on information from a manufacturer of such an analyzer, the cost for a diesel fuel sulfur analyzer would be about \$50,000, and the installation cost would be another \$5000.⁶³ Compared to the capital and operating cost of desulfurizing diesel fuel, the cost for this instrumentation is far below 1 percent of the total cost of this program.

i. Capital Cost Adjustment Factors

Capital costs are the one-time costs incurred by purchasing and installing new hardware in refineries. The capital costs supplied by the vendors, as discussed above, were designated to apply for a particular volumetric capacity in 1999 dollars. These costs are adjusted to match the volume of the particular case being analyzed using the “sixth tenths rule.”¹ According to this rule commonly used in the refining industry, the capital cost of a smaller or larger piece of equipment varies in proportion to the ratio of the smaller or larger capacity to the base capacity taken to some power, typically 0.6.

The calendar day volume is increased by 20 percent to size the hydrotreating unit for stream days which are the days which the unit is operating. This 20 percent calendar day to stream day factor is used to size the new hydrotreater to account for changes in day-to-day operations, for the difference in diesel fuel production throughout the year, and for treating offspec batches.

The capital costs are adjusted further to account for the offsite costs and differences in labor costs relative to the Gulf Coast. The factors for calculating the offsite costs and accounting for differences in labor costs is taken from Gary and Handewerk.⁶⁴ The offsite and labor factors from Gary and Handewerk are provided for different refinery sizes and different parts of the country, respectively. For the Tier 2 gasoline sulfur rule they were calculated for each PADD and we summarized those cost factors in Table V.C-13. The offsite factor provided by Gary and Handewerk is for a new desulfurization unit, but offsite costs are much lower for a revamped unit. We cut those factors in half to account for those units which are revamps of existing units.⁶⁵ The PADD-specific and national average cost factors are summarized in Table V.C-13 below.

¹ The capital cost is estimated at this other throughput using an exponential equation termed the “six-tenths rule.” The equation is as follows: $(S_b/S_a)^e \times C_a = C_b$, where S_a is the size of unit quoted by the vendor, S_b is the size of the unit for which the cost is desired, e is the exponent, C_a is the cost of the unit quoted by the vendor, and C_b is the desired cost for the different sized unit. The exponential value “ e ” used in this equation is 0.9 for splitters and 0.65 for desulfurization units (Peters and Timmerhaus, 1991).

Table V.C-13. Offsite and Location Factors Used for Estimating Capital Costs

	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5</i>
Offsite Factor - New Unit	1.26	1.26	1.20	1.30	1.30
- Revamped Unit	1.13	1.13	1.10	1.15	1.15
Location Factor	1.5	1.3	1	1.4	1.2

To account for other capital costs not accounted for by this cost estimate, such as some refiners having to debottleneck the amine and sulfur plants to address the additional sulfur removed and for other contingencies, capital costs were increased by 15 percent, a typical factor used for this type of analysis.⁶⁶ In addition, we modified this contingency factor based on comments which we received since the NPRM. The Association of Automobile Manufacturers provided comments on a cost study by the Department of Energy which estimated the cost of desulfurizing diesel fuel. These comments, made by an oil industry consultant, provided information on typical oil industry cost factors for starting up and operating new units in refineries percent.⁶⁷ One such cost factor is that the oil industry incurs a cost to start up a new unit which corresponds to about 3 percent of total capital costs. This factor was incorporated into our analysis by increasing our contingency factor from 15 to 18 percent.

The economic assumptions used to amortize capital costs over the production volume of low sulfur highway diesel fuel are summarized below in Table V.C-14.⁶⁸ These capital amortization cost factors are used in the following section on the cost of desulfurizing diesel fuel to convert the capital cost to an equivalent per-gallon cost.^m

^m The capital amortization factor is applied to a one time capital cost to create an amortized annual capital cost which occurs each and every year for the 15 years of the economic and project life of the unit.

Table V.C-14. Economic Cost Factors Used in Calculating the Capital Amortization Factor

<i>Amortization Scheme</i>	<i>Depreciation Life</i>	<i>Economic and Project Life</i>	<i>Federal and State Tax Rate</i>	<i>Return on Investment (ROI)</i>	<i>Resulting Capital Amortization Factor</i>
Societal Cost	10 Years	15 Years	0 %	7%	0.11
Capital Payback	10 Years	15 Years	39 %	6% 10%	0.12 0.16

ii. Fixed Operating Costs

Operating costs which are based on the cost of capital are called fixed operating costs. These are fixed because these costs are normally incurred whether or not the unit is operating or shutdown. Fixed operating costs normally include maintenance needed to keep the unit operating, buildings costs for the control room and any support staff, supplies stored such as catalyst, and insurance. The comments from the oil industry consultant referred to above were useful here for updating this portion of our analysis.

Various fixed operating cost factors were estimated based on comments which we received from the American Automobile Manufactures consultant referred to above.⁶⁹ Maintenance costs are estimated to be 3 percent of final capital costs. Other fixed operating costs are 1.5 percent of capital costs for buildings, 0.2 percent for land, one percent for supplies which must be inventoried such as catalyst, and 1 percent for insurance. These other fixed operating cost factors sum to 3.7 percent and, when combined with the 3 percent maintenance cost factor, sum to 6.7 percent. This total fixed cost factor of 6.7 percent is applied to the final capital cost (after including offsite costs and adjusting for location factor) to generate an annual fixed operating cost.

Annual labor costs are also estimated using the cost equation in the Oak Ridge National Laboratory (ORNL) refinery model. Labor cost is very small, on the order of one thousandth of a cent per gallon.

iii. Utility and Fuel Costs

Variable operating costs are those costs incurred to run the unit on a day-to-day basis, and are based completely on the unit throughput. Thus, when the unit is not operating, variable operating costs are not being incurred. Here, variable operating costs are determined using annual average diesel fuel production volumes instead of refinery specific production volumes to

avoid over- and under-counting of production when specific units are processing stored distillate after a shutdown or downgrading product when a unit is shutdown. The operating cost demands (utilities, hydrogen, and yield loss) are based on estimates from the desulfurization technology licensors described above. The basis for the values is 98 percent desulfurization (340 ppm sulfur reduced to 7 ppm sulfur on average) of the highway pool.

The utility cost inputs for our refinery model are from 1999 Energy Information Administration (EIA) information for each of the five Petroleum Administrative Districts for Defense (PADDs).⁷⁰

Yield loss is based on the volume of diesel volume lost times its market price offset by the additional volume of other products produced times their sales for resale market prices. A representative refinery price for diesel fuel after the desulfurization programs begins is derived by adding the estimated cost of desulfurizing diesel fuel for the highest cost producer to the resale price for diesel fuel from EIA. These cost factors are summarized in Table V.D-15.

Fuel gas is consumed in running furnaces for heating up streams including the reboilers used in distillation. Fuel gas cost is based on an estimation factor which is three dollars per million British thermal units (BTU) for PADD 3,⁷¹ one quarter higher than that for PADDs 1, 2 and 5, and half higher for PADD 4. Steam demand is converted to BTU demand on the basis that it is 300 pound per square inch (psi) steam, and that demand is presumed to be met with fuel gas, however, we increase the cost by a factor of two which is consistent with published cost estimation methodology.⁷² Producing steam is presumed to demand 809 BTU per pound of steam required.

Hydrogen costs are assumed to vary by PADD. The cost of hydrogen supply was estimated for PADD 3, and then increased for other PADDs that typically have higher costs. Hydrogen cost for PADD 3 is based on an average of refiners putting in their own hydrogen plants, which could cost as much as three dollars per thousand standard cubic foot (MSCF), and purchasing hydrogen as a commodity from a large hydrogen plant at a little more than one dollar per MSCF.⁷³ Based on this range of possible cost, PADD 3 would be expected to have access to hydrogen supplied at a cost of about two dollars per MSCF. PADD 4 is assumed to have to pay the more conservative cost of three dollars per MSCF, and the other PADDs are assumed to incur a cost between PADDs 3 and 4, which would be \$2.5 per MSCF. This analysis does not consider numerous other possibilities of providing hydrogen at a reduced cost by using hydrogen recovery technology (which would recover hydrogen from plant gas), or by increasing hydrogen production from the reformer by converting high pressure reformers to low or ultra low pressure reformers.

Table V.C-15. Summary of Costs From EIA Information Tables for 1999,* and Other Cost Factors

	<i>PADD 1</i>	<i>PADD 2</i>	<i>PADD 3</i>	<i>PADD 4</i>	<i>PADD 5</i>
Electricity (c/KwH)*	8.35	6.40	6.66	5.4	7.18
LPG (\$/Bbl)*	17.09	14.11	14.49	14.53	17.05
Highway Diesel (c/gal)*	53.1	55.9	51.5	62.4	64.0
Nonhighway Diesel (c/gal)*	49.3	55.7	48.6	60.4	58.9
Gasoline (\$/Bbl)*	27.0	25.9	24.9	28.9	30.0
Fuel Gas (\$/MMbtu)	3.75	3.75	3.0	4.5	3.75
Hydrogen Cost (\$/MSCF)	2.5	2.5	2.0	2.0	2.5

* c/KwH is cents per kilowatt-hour, \$/Bbl is dollars per barrel, c/gal is cents per gallon, \$/MMbtu is dollars per million British Thermal Units (Btu), \$/MSCF is dollars per thousand standard cubic feet.

Similar to the capital costs, we added a 10 percent operating cost safety factor to account for other operating costs which are beyond the operating cost of the desulfurization unit.⁷⁴ This factor accounts for the operating cost of processing additional hydrogen sulfide in the amine plant, additional sulfur in the sulfur plant, and other costs which may be incurred but not explicitly accounted for in our cost analysis. We then increased this factor by 2 percent to account for reprocessing of offspec material. For estimating capital costs, we estimated that 5 percent of the batches would be offspec and could not be blended down with lower sulfur product. However, since this material was desulfurized once already, the operating costs for reprocessing it would be much lower the second time around.

We also believe that refinery managers will have to place a greater emphasis on the proper operation of other units within their refineries not just the new diesel fuel desulfurization unit, to consistently deliver very low sulfur highway diesel fuel under the proposed cap standard. For example, meeting a stringent sulfur requirement will require that the existing diesel hydrotreater and hydrocracker units operate as expected. Also, the purity and volume of hydrogen coming off the reformer and the hydrogen plant would be important for effective desulfurization. Finally, the main fractionator of the FCC unit would have to be carefully controlled to avoid significant increases in the distillation endpoint, as a significant volume increase in sterically hindered compounds could be sent to the diesel hydrotreater with an increase in endpoint. The diesel hydrotreater may not be designed to desulfurize a significant increase in sterically hindered compounds. Improved operations management to control each of these units or situations could involve enhancements to the computer systems which control the

refinery operations, as well as improved maintenance practices.⁷⁵ Refiners may be able to recoup some or all of these costs through improved throughput. However, even if they cannot do so, these costs are expected to be less than 1 percent of those estimated below for diesel fuel desulfurization.^{76 77} No costs were included in the cost analysis for these potential issues.

f. Future Diesel Fuel Volumes

The volume of diesel fuel produced in future years is expected to increase consistent with projected future increases in diesel fuel demand. Estimating this increase is important as both the per-gallon costs and the aggregate costs are affected by the increase. Ignoring inflation and assuming that the prices of raw materials and products stay the same as in 1999, per-gallon costs would decrease somewhat with slightly improved economies of scale. However the aggregate capital and operating costs would increase as production volumes increase, although this increase is slower than the rate of increase in demand due to economies of scale.

To project future diesel fuel consumption, we relied on projections from the Energy Information Administration (EIA). EIA projects consumption of refined products into the future based both on historical production trends and on market factors likely to affect future demand. In the year 2000 Annual Energy Outlook, EIA projects that in 2006, highway diesel fuel consumption will be 39.5 billion gallons per year, with imports of 2.0 billion gallons per year. This level of diesel fuel consumption is 12.6 percent higher than today's consumption volume.

Since our analysis is performed on a refinery-by-refinery basis, it is important to project how each refinery's production of highway diesel fuel will change as consumption increases. Refiners tend to invest capital dollars in their refineries periodically for increasing the production volume of their products. This process of increasing refinery throughput is called debottlenecking. However, we have no way to project which refiners will invest to debottleneck their refineries for increased production, thus we cannot assign increases to specific refineries. Instead, we assume that each refinery will increase their production of highway diesel fuel by the same 12.6 percent between now and 2006. While highway diesel fuel consumption would be expected to increase again between 2006 and 2010, the change is modest, so we assumed that the 2006 volumes would apply in 2010 as well.

We made no changes in the volumes of diesel fuel processed to account for changes in wintertime blending of kerosene. Our cost projections are based on the volume of highway diesel fuel consumed today projected to the year 2006 and this assumes no changes in that volume in our final rule.ⁿ Thus, our cost projections include hydrotreating that volume of

ⁿ Actually, we assume that the total energy consumed in the form of diesel fuel remains constant. Diesel fuel volume consumed increases slightly because of a small decrease in the energy content of diesel fuel after additional hydrotreating.

kerosene which is currently blended into winter diesel fuel. Some of the kerosene which is blended into winter diesel fuel is blended at the refinery. This kerosene should be able to be added prior to the hydrotreater and desulfurized along with the rest of the highway diesel fuel pool. The rest of this kerosene is added at terminals or at other points within the distribution system. If this practice were to continue, then the kerosene distributed to these points would also have to meet the sulfur cap. Given this would likely involve hydrotreating more kerosene than actually needed to winterize diesel fuel, we believe that this practice would become much less common. Instead, we believe that cold flow additives would be used in greater amounts in lieu of kerosene blending downstream of the refinery. Cold flow improving additives are commonly used today in economic competition with kerosene blending and we believe that the cost differential between desulfurizing kerosene and blending in cold flow additives to achieve the same effect is negligible. Thus, assuming that the difference in cost of cold flow additives and kerosene blending is negligible, we expect that diesel fuel suppliers would reduce the current amount of kerosene blending and increase additive use at no additional cost and avoid the need to hydrotreat kerosene which may be used in other applications than highway diesel engines to less than 15 ppm sulfur.

2. Projected Refinery Costs of Meeting the 15 ppm Sulfur Cap

For each of 121 refineries currently producing highway diesel fuel, the capital and operating cost inputs described above were combined together in our refinery model along with the fractions of the various blendstocks for each refinery to estimate the cost of desulfurizing highway diesel fuel from a base sulfur level of 340 ppm to an average of 7 ppm sulfur to meet the 15 ppm cap standard.^o

The per-refinery capital and operating costs, and the per-gallon cost for refineries were classified into small and non-small refinery categories and are summarized in Table V.C-16 below.

^o Grass roots capital costs were determined based on new equipment required while grass roots operating costs were assumed to be the same as a revamped unit.

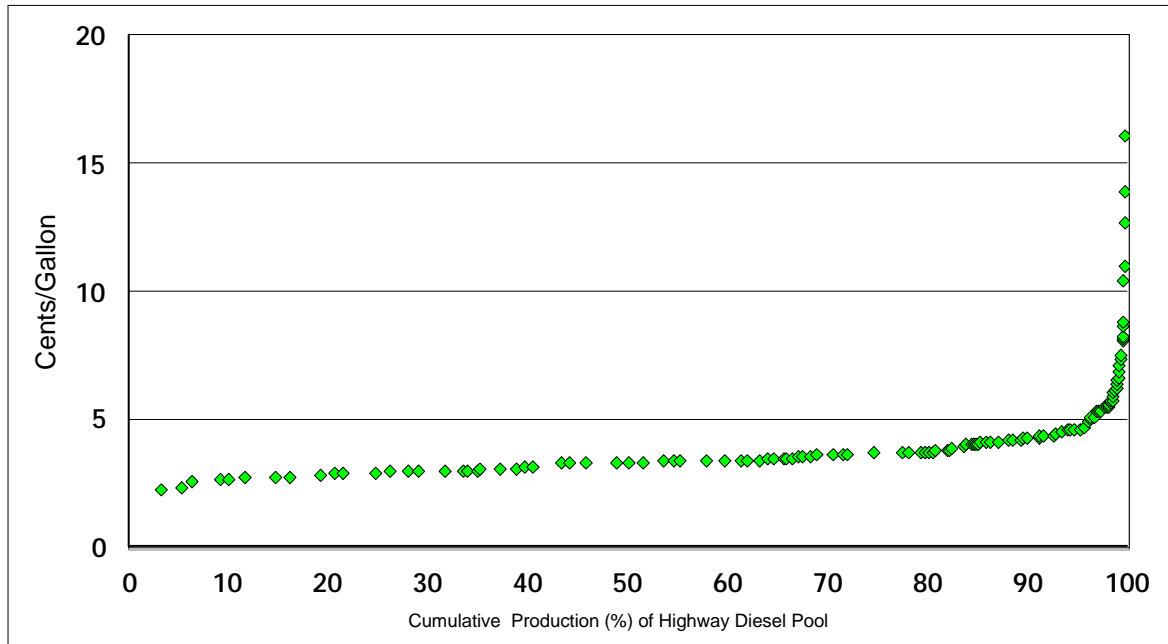
Table V.C-16. Estimated Per-Refinery Capital, Operating and Per-Gallon Cost for Full^A Implementation of Desulfurizing Highway Diesel Fuel to Meet a 15 ppm Cap Standard (1999 Dollars, 7% ROI before taxes)

	<i>Average of Nonsmall Refineries</i>	<i>Average of Small Refineries</i>	<i>National Average</i>
Capital Cost (\$Million)	52	14	44
Operating Cost (\$Million/yr)	9.6	0.5	7.9
Per-Gallon Cost (c/gal)	4.2	5.0	4.3

^A Based on the assumption that each refineries costs will be comprised of; 80% for revamping a refiner's existing hydrotreater unit and 20% for building a new grassroots unit. Grass roots units capital costs were determined based on new equipment required while grass roots operating cost were assumed to be the same as a revamped unit. National average refinery costs includes refineries classified as small. Capital costs are total aggregate per refinery in each category.

Table V.C-16 shows that, on average for full implementation of the 15 ppm highway diesel fuel sulfur cap standard, non small refineries would incur initial capital cost of \$52 million to meet the proposed sulfur cap. In addition, these refineries would incur an average of \$9.6 million per year in operating costs. The capital and operating cost for typical small refineries would be much lower, \$14 million and \$0.5 million per year per refinery, respectively, but due to poorer economies of scale their installed capital costs would be higher on a per-gallon basis. Our cost estimates bear this out as the per-gallon cost to the average small refinery is about 20 percent higher (about 1.0 cents per gallon) than the per-gallon cost of the average nonsmall refinery, thus, our analysis projects that small refineries are more challenged than the refineries which treat a larger volume of diesel fuel. The per-gallon cost for all of the refineries participating varied and can be viewed in Figure V.C-1. Inspection of the graph reveals that for the 121 refineries, only four to five volume percent of the total highway pool have high costs that exceed 5 cents per gallon.

Figure V.C-1. Refinery Specific Costs for Fully Implemented 15 ppm Sulfur Cap Standard



^a Costs per treated volume of highway diesel for 121 refineries, 1999 dollars and capital is amortized 7% ROI before taxes.

Refineries with LCO and coker gas oils had higher costs than those processing straight run diesel. LCO feed stocks had the highest hydrotreater costs with an average feedstock based incremental cost of 6.55 cents per gallon treated. Likewise, coker gas oil and straight run diesel had average incremental feedstock costs of 4.72 and 3.47 cents per gallon, respectively. The costs for LCO and coker feed stocks were higher due to the increased capital and operating cost associated with treating these feed stocks, see Table V.C-17.

**Table V.C-17. Costs for Treating LCO, Coker, and Straight Run Diesel Feedstocks
(1999 Dollars and 7% before tax ROI)**

	<i>LCO^a</i>	<i>Coker^a</i>	<i>Straight Run Diesel^a</i>
Cost to Treat Feedstock c/gal	6.55	4.72	3.47

^a Based on the assumption that each refinery's costs will be comprised of; 80% for revamping a refiner's existing hydrotreater unit and 20% for building a new grassroots unit. Grass roots units capital costs were determined based on new equipment required while grass roots operating costs were assumed to be the same as a revamped unit.

In Chapter 4, we discussed the temporary compliance option and small refinery hardship provisions with respect to refineries initiating compliance to the new highway diesel sulfur cap standard in either year 2006 or 2010. The refining industry is expected to take advantage of the temporary compliance option with the lowest cost producers complying during 2006-2009 and the highest cost producers complying starting in 2010. In each PADD for year 2006, the lowest cost refineries were added to the 2006 year pool until the volume requirement was met for producing 80% of the respective PADDs' 15 ppm temporary compliance sulfur diesel pool. In addition, for each PADD, small refineries with costs that placed them in the 80% low cost temporary compliance pool were considered to enter the market in year 2006. Cost for 2006 also included small refineries that were projected to select the option that allows extending the implementation date of the Tier 2 gasoline sulfur requirement. All remaining refineries which were not classified as being in the 2006 year pool were considered to comply in year 2010.

Table V.C-18. Overall Estimated Per-Refinery Capital, Operating and Per-Gallon Cost for Years 2006 and 2010 for Implementation of Desulfurizing Highway Diesel Fuel to Meet a 15 ppm Cap Standard (1999 Dollars, 7% ROI before taxes)

	<i>Year 2006 Average Refinery ^a</i>	<i>Year 2010 Average Refinery ^a</i>
Capital Cost (\$Million)	61	24
Operating Cost (\$Million/yr)	11.8	6.41
Per-Gallon Cost (c/gal)	4.1	5.0

^a Based on the assumption that each refinery’s costs will be comprised of 80% of the cost for revamping the refinery’s existing hydrotreater unit and 20% for building a new grassroots unit. Grass roots units capital costs were determined based on new equipment required while grass roots operating costs were assumed to be the same as a revamped unit.

Our analysis of the average refinery capital, operating costs and average per gallon cost is summarized in Table V.C-18. On average, the 63 refineries entering the year 2006 pool would have capital costs of \$61 million per refinery. The average capital costs for refineries that newly enter the 15 ppm highway pool in year 2010 are \$24 million per refinery. These costs reflect that the large refineries have lower overall costs due to economies of scale and will enter the highway diesel market in year 2006. By delaying the revamp costs for the highest cost diesel hydrotreater units until 2010 the refinery industry will be able to defer \$1.4 billion dollars over a four year period.

Table V.C-19 shows the aggregate capital and operating costs for the U.S. refining industry that were developed for 2006-2030. To calculate the aggregate capital cost, the total capital cost for each of the 121 refineries which we estimated in our refinery model was summed together. With the temporary compliance option and small refinery hardships provisions, capital costs for the years of 2006 and 2010 were \$3.9 and \$1.4 billion, respectively. Capital costs for complying in years 2006 and 2010 were spread to reflect project installation according to the following; one third of the capital costs assigned to the one year period before the compliance date with the remaining two thirds costs assigned to the two year period before the compliance date. Capital costs which are estimated to total \$5.3 billion are presumed to be incurred in 2004, 2005, 2006, and 2008, 2009, and 2010 as the desulfurization units are installed in the refineries. To maintain future program compliance requirements, a second round of capital cost investments is assumed to occur 15 years later as the desulfurization units installed are replaced at the presumed end of their useful life. Aggregate capital costs increase for the 2nd round of investment in 2019 - 2025 relative to 2004 - 2010 due to increased fuel production volumes required to meet growth in diesel demand. We then calculated the yearly aggregate operating

costs based on the projected diesel consumption in 2006-2030 shown in Table V.C-19. The aggregate operating cost is calculated by simply multiplying the average per-gallon operating cost and the aggregate volumetric consumption together. The aggregate operating costs increase each year due to the constant increase in growth in diesel demand. These costs are summarized in Table V.C-19.

Table V.C-19. Projected U.S. Aggregate Operating and Capital Cost of Desulfurizing Highway Diesel Fuel to Meet a 15 ppm Cap Standard (1999 Dollars, 7% ROI before taxes)

<i>Year</i>	<i>Projected 7 ppm Diesel Fuel Production^a (Billion Gals)</i>	<i>Projected Aggregate Operating Cost (\$Billion)</i>	<i>Projected Aggregate Capital Cost (\$Billion)^a</i>	<i>Projected Total Aggregate Cost (\$Billion)</i>
2004	-		1.3	1.30
2005	-		1.9	1.90
2006	39.5*0.58	0.64	0.7	1.34
2007	40.1	1.04	-	0.75
2008	40.7	1.05	0.5	1.55
2009	41.3	1.07	0.7	1.77
2010	41.9	1.11	0.2	1.31
2011	42.6	1.13		1.02
2012	43.2	1.15		1.04
2013	43.8	1.17		1.05
2014	44.5	1.18		1.07
2015	45.2	1.20		1.09
2016	45.8	1.22		1.10
2017	46.5	1.24		1.12
2018	47.2	1.26		1.14
2019	47.9	1.27	1.5	2.77
2020	48.7	1.30	2.2	3.5
2021	49.4	1.31	0.8	2.11
2022	50.1	1.33		1.20
2023	50.9	1.35	0.6	1.95
2024	51.6	1.37	0.8	2.17
2025	52.4	1.39	0.3	1.69
2026	53.2	1.42		1.28
2027	54.0	1.44		1.30
2028	54.8	1.46		1.32
2029	55.6	1.48		1.34
2030	56.5	1.50		1.36

^a For U.S. refiners only.

Table V.C-19 shows that the aggregate capital cost for complying with the proposed 15 ppm highway diesel sulfur cap is expected to total about \$5.3 billion spread out over seven years. This level of capital expenditure is estimated to be slightly more than the capital expenditures expected to be made by the U.S. refining industry for complying with gasoline sulfur standards, (see Section B of Chapter IV). We believe that these costs are not excessive. For example, during the early nineties the U.S. refining industry invested over twenty billion dollars in capital for environmental controls for their refining and marketing operations; ⁸⁵ this cost represented about one half of the total capital expenditures made by refiners for the downstream operations of their refineries. Considering the effects of inflation we believe that a program requiring the refining industry to spend about \$5.3 billion is not overly burdensome from an economic perspective. The relative value of the costs and benefits of this program are discussed in Chapter VII.

As stated above, we also estimated the per-gallon cost of this program based on different capital cost amortization premises. In Table V.C-20 below, projected average per-gallon costs of complying with the proposed sulfur cap for small refineries and non-small refineries are shown based on various rates of return on investment (ROI) before taxes. The first row of costs shown are our estimates of the costs to society, which utilize a seven percent before tax ROI. We then present two additional cost estimates which are based on six and ten percent after tax ROIs. These latter rates of return are indicative of the economic performance of the refining industry over the past 10-15 years.

Table V.C-20. Per-Gallon Cost for Desulfurizing Highway Diesel Fuel to Meet a 15 ppm Cap Standard Based on Different Capital Amortization Rates (1999 Dollars)

	<i>Average Cost of Non Small Refineries ^a (c/gal)</i>	<i>Average Cost of Small Refineries (c/gal)</i>	<i>U.S. Average Cost (c/gal)</i>
Societal Cost 7% ROI before Taxes	4.2	5.0	4.3
Capital Payback (6% ROI, after Taxes)	4.3	5.2	4.4
Capital Payback (10% ROI, after Taxes)	4.6	5.8	4.7

^a Average refinery costs excludes refineries classified as small.

In Chapter 4, we addressed the ability of the refining industry to produce adequate supplies of highway diesel fuel to avoid shortages under the 15 ppm highway diesel fuel cap standard. First, the temporary compliance option and small refinery hardship provisions substantially enhances supplies of highway diesel fuel by allowing roughly 22% of highway diesel fuel to continue to meet the 500 ppm cap. This gives roughly 58 refineries four more years before needing to invest in desulfurization equipment to meet the 15 ppm standard. By the time these refiners need to decide on a desulfurization technology, those units built in 2006 will have been operating for 1-2 years, providing commercial data upon which to conduct a comparison. This data will help these refiners to borrow money, if necessary, to pay for the new equipment.

The other factor easing highway diesel supplies is the ability of a number of refiners to economically produce 15 ppm fuel from current nonhighway diesel fuel blendstocks. To quantify this factor, we developed a model to estimate the cost to each refinery of desulfurizing all their existing nonhighway diesel fuel to an average sulfur level of 7 ppm (i.e., that needed to ensure compliance with the 15 ppm cap). These costs were developed for all U.S. refineries that currently produce nonhighway diesel. Especially in cases where grass roots refinery modifications are necessary to process current highway diesel fuel to 15 ppm sulfur, there are no competitive disadvantages, and in some cases improved economies of scale by investing to convert current nonhighway diesel to highway diesel. As was the case when estimating each refinery's cost to produce 15 ppm fuel from its highway diesel blendstocks, the cost for processing nonhighway diesel blendstocks were based on volume throughput and feedstock compositions. Again, as was done for their highway diesel blendstocks, each refinery's nonhighway blendstock composition was estimated from distillate pool information taken from the data provided by EIA for 1998 and 1999. These processing costs were reduced by using the average price differential between highway and nonhighway diesel fuel of EIA⁸³ and Muse Stancil & Co's⁸⁴ product pricing data. The EIA data was based on historical price difference between highway and nonhighway diesel fuel at the refinery gate while Muse Stancil & Co's pricing data was based on the historical price difference between low and high sulfur No. 2 Oil of batches being transported by pipeline to market. Using this average for credit is appropriate, since the highway diesel fuel produced from nonhighway diesel blendstocks would command the price of highway diesel fuel under the new sulfur cap, compared not to the price of highway diesel fuel prior to the cap, but to the price of nonhighway diesel fuel prior to the cap. See Table V.C-21.

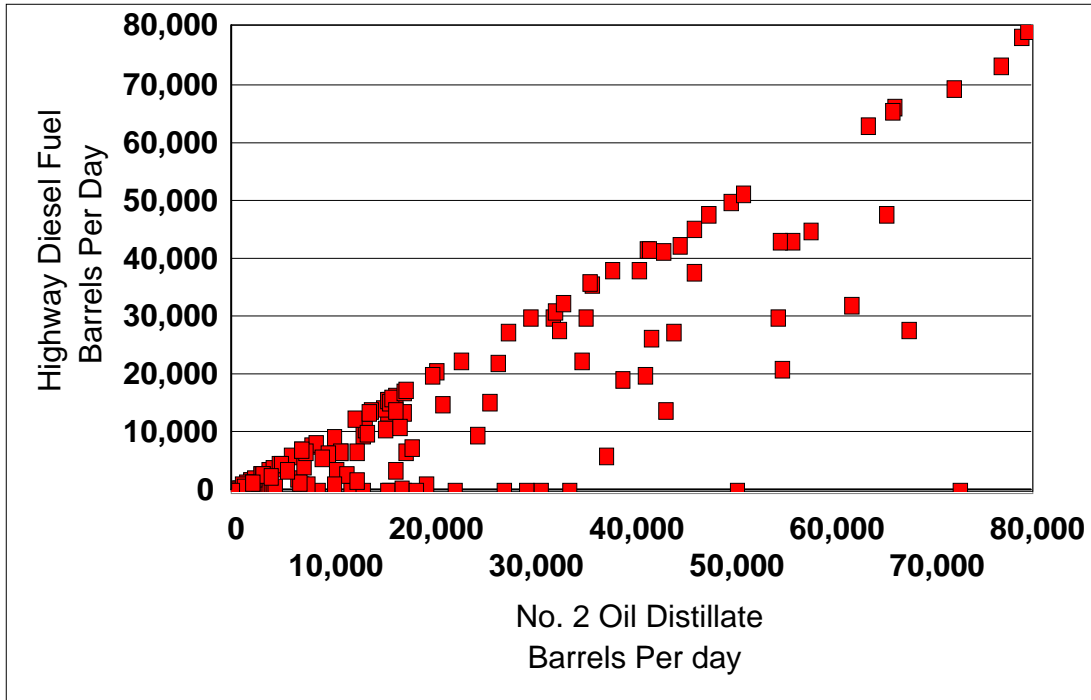
Table V.C-21. PADD-Average Price Difference Between 500 ppm Highway and Non-Highway Diesel (1999 Dollars, 7% ROI before taxes)

	<i>Muse, Stancil's^a Delta Price Between Low and High Sulfur No. 2 Oil (c/gal)</i>	<i>EIA^a Delta Price Between Highway and Nonhighway Diesel (c/gal)</i>	<i>Average of EIA and Muse Stancil & Co's data (c/gal)</i>
PADD 1	2.0	1.6	1.8
PADD 2	0.0	1.8	0.9
PADD 3	2.8	1.6	2.2
PADD 4	2.1		2.1
PADD 5	3.9	5.0	4.5

^a EIA data based on 1995-1999 average price difference between low and high sulfur diesel fuel. Muse, Stancil & Co. prices from Alternate Markets for Highway Diesel Fuel Components, September 2000 and are based on 1995-1999 average price difference between low and high sulfur No.2 Oil. Overall volume weighted highway and nonhighway diesel cost adjustment for USA PADD regions is 2.2 c/gal.

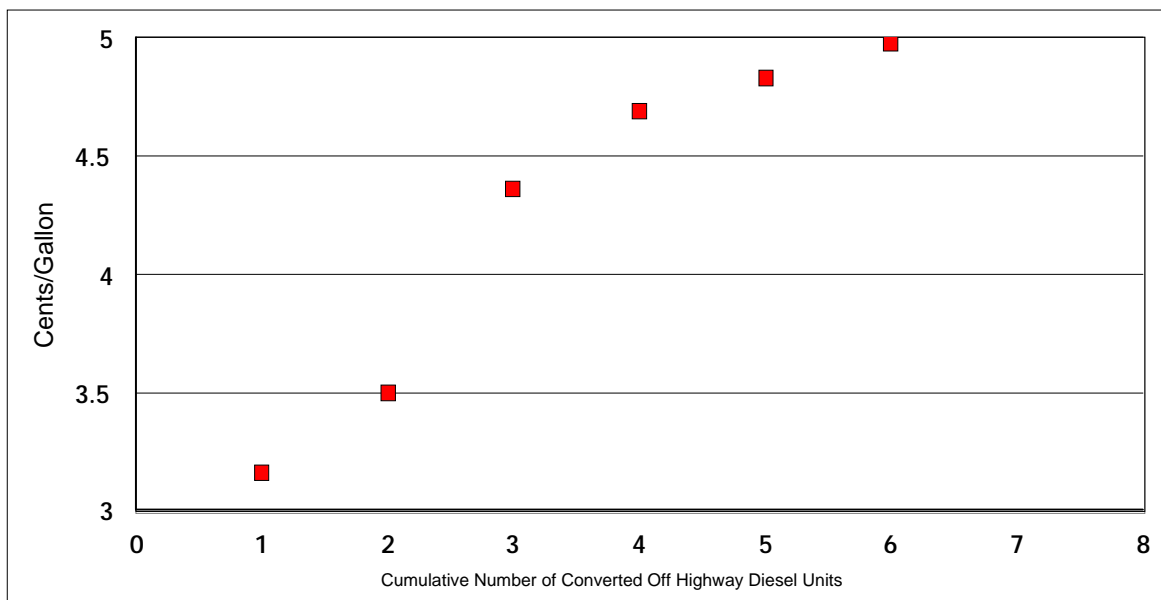
Through this analysis, we found that a number of refineries could produce highway diesel fuel from nonhighway diesel blendstocks in separate hydrotreating units at a cost which was competitive with other refineries in their PADD. In these cases, the volume of nonhighway diesel fuel was large so, regardless if the refineries are producing highway or not, we assumed that these would be new grassroots units. In our model, the nonhighway diesel blendstocks are processed in a new grass roots unit, while the highway diesel blendstocks are processed in either a revamped or grassroots unit, according to an 80:20 ratio. In reality, a refinery deciding to process both its highway and nonhighway diesel blendstocks to meet a 15 ppm cap would likely do so in a single grassroots unit sized to process both current products. We compared the cost of such a single larger grassroots unit to the two unit approach for a few refineries and found that the single grassroots unit would be less costly. Thus, the costs used in this analysis, which assume that the refinery would process its nonhighway diesel blendstocks in a separate unit, are likely to be slightly overestimated. For hydrotreater highway units with large volumes of highway and small volumes of nonhighway diesel, combining the two production streams as feed for revamping the existing hydrotreater would provide economies of scale and would reduce the overall costs in generating 15 ppm sulfur cap highway fuel. The costs used in this analysis did not consider this option. Figure V.C-2 illustrates that additional distillate volume would be available as feedstock to convert to highway diesel. Number 2 Oil in this figure is the summation of highway and nonhighway diesel fuel per refinery.

Figure V.C-2. Refinery Specific Production Rates of Highway Diesel versus No. 2 Oil Distillate Pool ^a



^a Per Annum Refinery Specific plot of Highway Diesel Production volume versus total No. 2 Distillate volume produced by the refinery. Based on EIA refinery production data for 1998/1999.

Figure V.C-3. Lowest Refinery Costs for Converting NonHighway to 15 PPM Highway Diesel Fuel ^A



^A Costs per treated volume of nonhighway diesel, 1999 dollars, and 7% ROI before taxes.

Overall, we found 2 refineries which produce essentially no highway diesel fuel today which could meet the new 15 ppm standard for less than 5.0 cents per gallon. Production from these refineries would increase nationwide highway diesel fuel production by 2 percent. We also found that 4 other refineries could increase production of highway diesel fuel from their nonhighway diesel fuel blendstocks for less than 5.0 cents per gallon. Production from these 4 refineries would increase highway diesel fuel production by an additional 5 percent. See Figure V.C-3 for plot of the cost of these nonhighway diesel fuel converted units.

A sensitivity analysis was then performed to estimate the cost of meeting the 15 ppm sulfur cap if some of the blendstocks currently being used to produce nonhighway diesel fuel were used to produce 15 ppm diesel pool and some of the refineries currently producing highway diesel fuel shifted their fuel to the nonhighway diesel fuel market.

We imposed a number of restrictions on such shifts. First, 15 ppm diesel fuel produced from nonhighway blendstocks used in PADDs 3, 4 and 5 had to be produced in those PADDs,

with the further restriction that no such fuel could be transported to either Hawaii or Alaska from outside of those states. Second, 15 ppm diesel fuel produced from nonhighway blendstocks used in PADD 2 had to either come from within the PADD or could come from PADD 3 if it displaced higher cost highway diesel fuel in the southern portion of PADD 2. Practically, this limited any additional transfers of 15 ppm fuel from PADD 3 to PADD 2 to a very small amount (0.05 percent of current PADD 2 highway diesel fuel production). Finally, 15 ppm diesel fuel produced from nonhighway blendstocks in PADD 3 was allowed to displace current highway diesel fuel produced in PADD 1. PADD 3 currently sends sizeable amounts of both highway and nonhighway diesel fuel to PADD 1. The relative amount of highway diesel fuel produced in PADD 3 could therefore easily increase and the amount produced in PADD 1 decrease without changing the total volume of diesel fuel transported. We found that about 14% of current PADD 1 highway diesel fuel production could be made in compliance more economically from nonhighway diesel blendstocks in PADD 3. After considering these restrictions in the substitution of nonhighway to highway diesel fuel, only 5 percent of the total 15 ppm highway production volume is shifted to replace the high cost highway producers. This is less than the 7 percent of nonhighway diesel fuel which we found available with estimated costs less than 5 cents per gallon. Table V.C-22 highlights the cost difference between the nonhighway hydrotreaters and the highway producers which were supplanted by the nonhighway producers.

**Table V.C-22. Costs Under Nonhighway Production Shift Scenario
(1999 Dollars, 7% ROI before taxes)**

	<i>Higher Cost Highway Units^a</i>	<i>15 ppm Diesel from NonHighway</i>
Number of Refineries	17	6
Capital Cost, Per Refinery (\$Million)	12	29
Operating Cost, Per Refinery (\$Million/yr)	1.5	2.5
Per-Gallon Cost (c/gal)	6.3	4.5

^a Based on the assumption that each refinery’s costs will be comprised of 80% of the cost for revamping the refinery’s existing hydrotreater unit and 20% for building a new grassroots unit. Grass roots units capital costs were determined based on new equipment required while grass roots operating costs were assumed to be the same as a revamped unit.

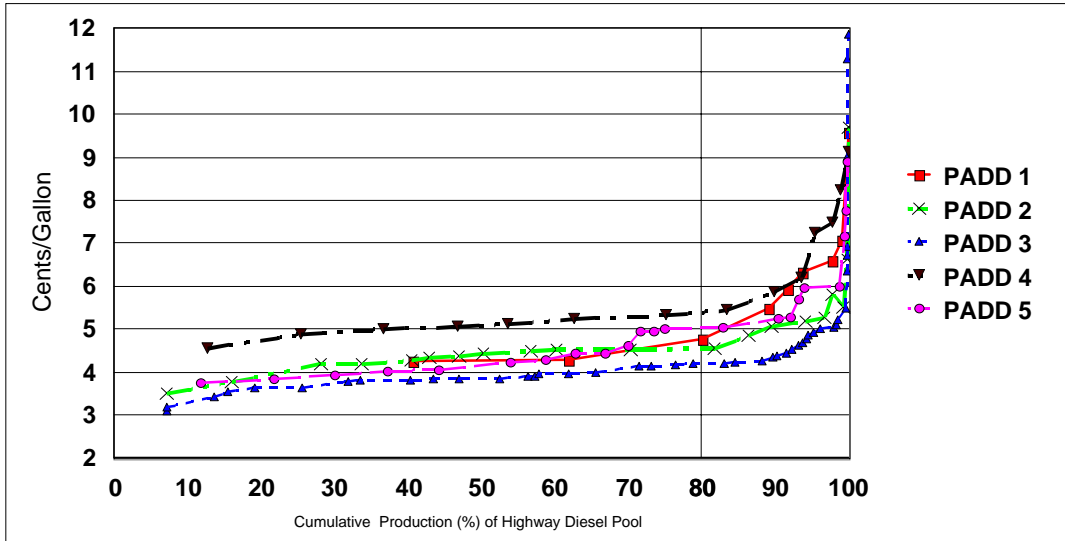
The effect of this shift on average costs and total capital cost are very small. These are shown in Table V.C-23. The effect of this shift on the maximum cost in each PADD is more significant, particularly in PADDs 1 and 5. In these PADDs, it would be very expensive to bring a very small percent of current highway diesel fuel production into compliance with the 15 ppm cap, primarily because of poor economies of scale. Refer to Section IV, Table IV.A-7 which compiles the PADD specific reduction in maximum costs attributed to using nonhighway to make 15 ppm sulfur cap highway diesel. With supplemental 15 ppm fuel from current nonhighway blendstocks, these small quantities of current highway fuel can be shifted to the nonhighway diesel fuel market with no loss of supply of highway diesel fuel or flooding of the nonhighway markets. Figures V.C-4 and V.C-5 illustrate the use of supplemental nonhighway to reduce maximum costs in each PADD. Figure V.C-4 represents the distribution of refinery cost by PADD for the case where production shifts were not presumed to occur between nonhighway and highway diesel producers. Whereas Figure V.C-5 represents a similar plot where production shifts are allowed. Comparing the two figures demonstrates that production shifts from nonhighway to highway would eliminate the highest cost producers. Both figures reveal that, for each PADD, costs are relatively constant for highway production volumes from 0 to 80 percent with the costs escalating for volumes greater than 80 percent. Inspection of the Figures also show that PADD 4 has the highest costs while PADD 3 has the lowest costs for producing highway diesel fuel which meets the 15 ppm sulfur cap standard.

Table V.C-23. Estimated Costs of Nonhighway Production Shift Scenario versus Current Highway Producer Scenario to Meet 15 ppm Highway Diesel Fuel Cap Standard (1999 dollars, 7% ROI before taxes)

	<i>Nonhighway Units Shift Scenario ^a</i>	<i>Current Highway Units Scenario</i>
U.S. Aggregate Capital Cost (\$Billion)	5.4	5.3
U.S. Aggregate Operating Cost (\$Million/yr)	970	960
Average Refinery Capital Cost (\$Million)	51	44
Average Refinery Operating Cost (\$Million/yr)	9.1	7.9
Average Per-Gallon Cost (c/gal)	4.2	4.3

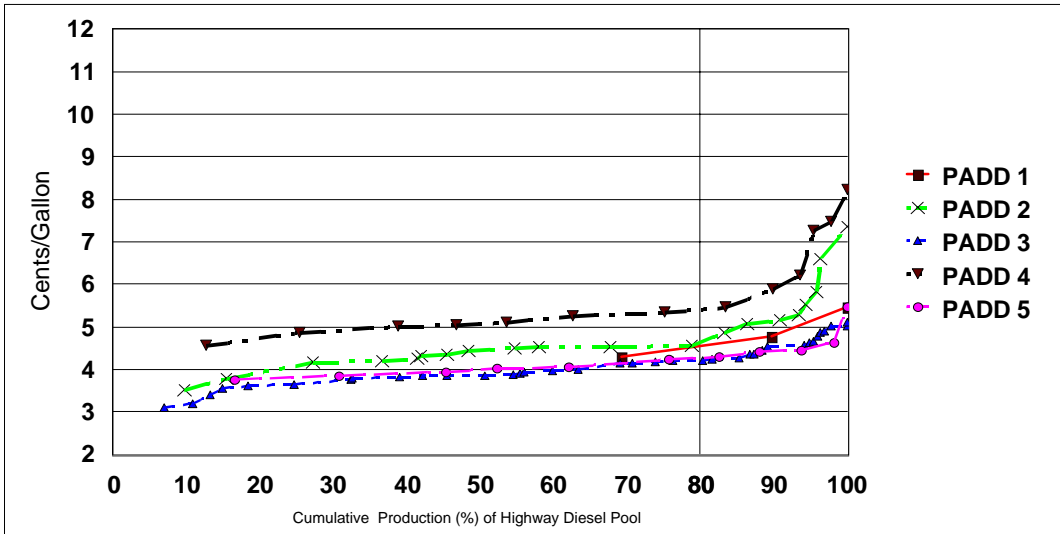
^a Based on the assumption that each refinery's costs will be comprised of 80% of the cost for revamping the refinery's existing hydrotreater unit and 20% for building a new grassroots unit. Grass roots units capital costs were determined based on new equipment required while grass roots operating costs were assumed to be the same as a revamped unit.

Figure V.C-4. Refinery Costs per PADD for Current Highway Units Scenario for Meeting the 15 ppm Sulfur Highway Diesel Fuel Cap Standard ^a
 (1999 dollars, 7% ROI before taxes)



^a Costs excludes Hawaiian, Alaskan, and small refineries projected to take the gasoline extension option. Based on the assumption that each refinery's costs will be comprised of 80% of the cost for revamping the refinery's existing hydrotreater unit and 20% for building a new grassroots unit. Grass roots units capital costs were determined based on new equipment required while grass roots operating costs were assumed to be the same as a revamped unit.

Figure V.C-5. Refinery Costs per PADD under Converted NonHighway Units Shift Scenario for Meeting the 15 ppm Highway Diesel Fuel Cap Standard^a
 (1999 dollars, 7% ROI before taxes)



^a Costs excludes Hawaiian, Alaskan, and small refineries projected to take the gasoline extension option.

a. Other Cost Estimates for Desulfurizing Highway Diesel Fuel

A number of cost estimates of the 15 ppm highway diesel fuel sulfur standard were submitted as part of the comments on the proposed rulemaking. Mathpro used a notional refinery model to estimate the national average costs of the proposed standard for the Engine Manufacturers Association (EMA). For the American Petroleum Institute (API), Charles River Associates, along with Baker and O'Brien, used the Prism refinery model to estimate the cost of U.S. refineries to produce highway fuel in the U.S. EnSys used the Oak Ridge National Laboratory PADD 3 refinery model to estimate costs for the Department of Energy(DOE). Finally, the National Petroleum Council (NPC) used the Mathpro refinery modeling work to estimate a cost for meeting a less stringent standard. The cost estimates from each of these studies is presented in the respective sections and, if appropriate, compared to our cost analysis.

Mathpro's Cost Analysis for EMA

In a study conducted for the EMA,⁷⁸ MathPro, Inc. estimated the cost of desulfurizing diesel fuel to meet a 15 ppm highway diesel fuel sulfur cap standard. MathPro assumed that desulfurization would occur entirely through severe conventional hydrotreating, and refining operations and costs were modeled using their ARMS modeling system with technical and cost data provided by Criterion Catalyst Company LP, Akzo-Nobel Chemicals Inc., and Haldor Topsoe, Inc. The resulting cost estimates were created based on what Mathpro terms a "notional" refinery. The notional refinery is configured to be typical of the refineries producing highway diesel fuel for PADDs 1, 2, and 3, and also represent the desulfurization cost for those three PADDs based on the inputs used in the refinery model. The Mathpro notional refinery model maintained production of highway diesel fuel at their base levels.

Mathpro made a number of estimates in their study to size their diesel desulfurization units for estimating the capital cost, and these estimates were similar to those included in our methodology. The calendar day volume was adjusted to stream day volume using a 10 percent factor to account for variances in day-to-day operations, and another 10 percent to account for variance in seasonal demand. In addition, Mathpro applied a factor which falls somewhere in the range of 1 - 8 percent for reprocessing off-spec material to meet a number of different sulfur targets. Since meeting a 15 ppm cap standard is a relatively stringent sulfur standard compared to the sulfur levels studied, Mathpro likely assumed the desulfurization unit would be sized larger by 5 - 8 percent. Onsite investment was adjusted to include offsite investment using a factor of 1.4. In the final report, capital costs were amortized at a 10 percent after tax rate of return.

There are several differences between our cost analysis and the cost analysis made by Mathpro. First, the MathPro costs are based on a 10 percent ROI after taxes. As stated above, our costs are calculated based on a 7 percent rate of return on investment (ROI) before taxes, so

to compare our cost analysis with the cost analysis made by Mathpro, we adjusted the Mathpro costs to reflect the rate of return on capital investment which we use. Second, the Mathpro study did not attempt to project how much of highway diesel fuel will be produced by revamping existing diesel hydrotreaters versus installing new grassroots units. Instead, Mathpro provided cost estimates for both revamped and grassroots units. This range of costs is presented here, and we include a cost which represents 80 percent revamp and 20 percent grassroots units. Third, the MathPro estimate includes a cost add-on (called an ancillary cost) for reblending and reprocessing offspec diesel fuel or for storing nontreated diesel fuel. While this is conceptually an appropriate adjustment, it appears that some of the reblending costs in the MathPro study appear to be transfer payments,^p not costs. Fourth, MathPro assumed that all new hydrogen demand is met with new hydrogen plants installed in the refinery, which does not consider the advantage of hydrogen purchased from a third party which can be produced cheaper in many cases. As a result, their hydrogen cost may be exaggerated, which would tend to increase costs. Finally, it should be noted that the MathPro study did take into consideration the need for lubricity additives, but did not address costs that might be incurred in the distribution system. Thus, in a comparison of our costs with Mathpro's, we will include our cost estimate for adding the appropriate amount of lubricity. A comparison of Mathpro's cost and our cost to desulfurize highway diesel fuel to meet a 15ppm sulfur cap standard is shown below in Table V.C-24.

Table V.C-24. Comparison of Mathpro's and EPA's Costs for Meeting a 15 ppm Highway Diesel Fuel Sulfur Cap Standard (7% ROI before taxes)

	<i>Mathpro's Cost</i>	<i>EPA's Cost</i>
Per-gallon Cost	4.2 - 6.1 (4.6)	4.3
Capital Cost	3.4 - 6.1 (3.9)	5.3

Cost assumes the addition of lubricity additives, but no distribution costs.

Lower end of the range in per-gallon costs assumes 100 percent revamped equipment; upper end assumes all new equipment; EPA costs and the Mathpro costs in parentheses assume 80 percent revamps and 20 percent new units.

Charles River and Baker and O'Brien Study for API

Charles River Associates and Baker and O'Brien (heretofore referred to as CRA), in a study for API, analyzed the impacts of a 15 ppm highway diesel fuel sulfur cap standard on the U.S. oil industry. Nonroad diesel fuel was also reduced to 350 ppm, probably to meet an assumed future 500 ppm cap standard. CRA used the Prism refinery model along with their own

^p A transfer payment is when money changes hands, but no real resources (labor, natural resources, manufacturing etc.) are consumed.

estimates of hydrotreating costs to estimate the cost to each refinery of meeting the cap standard taking into account the estimated fractions of the various blendstocks which comprise highway diesel fuel and the quality of crude oil used by each refinery. CRA based their cost analysis on desulfurization technology (not on ring opening technology, and hydrogen consumption was similar to Mathpro's), but estimated that 40 percent of refiners would build new hydrotreating units with the balance of refiners revamping their existing units.

CRA surveyed the major refiners which produce about half of the total amount of highway diesel fuel produced in the U.S. asking if they anticipated producing highway diesel under a 15 ppm sulfur cap standard. Refiners responded with a range of responses. Some said that they would increase or maintain their highway diesel fuel production, while others said that they would decrease their production. CRA concluded from their analysis of the survey responses that highway diesel production would decrease by 9 to 11 percent. Since this was an estimated shortfall in domestic highway diesel fuel production associated with a lack on investment by a large number of refineries, only imports were presumed to be available to make up the difference.

CRA's estimates for sizing their diesel desulfurization units are summarized here. First, each unit size is increased by 20 percent to account for sizing a unit's calendar day volume to a stream day volume, which addresses variances in daily or seasonal highway diesel production output, and unit downtime. Then, CRA assumed, based on a study by Baker and O'Brien, that 10 percent of the highway diesel fuel being produced would be downgraded to nonhighway diesel due to contamination in the distribution system. To make up for that loss in volume, each refinery's diesel desulfurization unit size and the operating costs were increased by 10 percent to account for this projected volume shortfall. The unit size was increased by another 10 percent to account for reprocessing of offspec batches. Thus, after consolidating all these factors, each refinery unit was sized 40 percent larger than calendar day volume. Then, the calculated capital costs were adjusted upward by 20 percent to cover contingencies. In estimating per-gallon costs, CRA amortized the capital costs at a 10 after tax percent rate of return.

CRA did not directly provide an average cost estimate for their analysis, estimate an average cost from CRA's report, we examined CRA's cost curve which plots individual cost for each refinery in the U.S., which CRA assumes are continuing to produce highway diesel fuel, against cumulative highway diesel fuel production. The average cost for the U.S. refineries is about 6.2 c/gal. CRA did not attempt to determine a diesel desulfurization cost for the balance of the highway diesel fuel which would have to be made up by imports.

We have a couple of observations and comments on the analysis by CRI. First, the study incurred costs for desulfurizing nonroad diesel fuel to meet a 500 ppm cap standard, however, the study's report did not provide the reader with information to determine what impact desulfurizing nonhighway might of had on the per-gallon cost of desulfurizing highway diesel fuel. CRA assumed that this 500 ppm fuel would be produced by blending 8 ppm sulfur highway diesel fuel

and 3000 ppm nonroad diesel or heating oil. While, much of this production was assumed to occur due to mixing in the distribution system, an unknown amount of 500 ppm fuel was produced at refineries. Desulfurization costs are not linear, as shown by CRA's own study. Thus, any blending of 15 ppm sulfur highway diesel fuel with non-desulfurized heating oil at refineries was much more costly than simply hydrotreating nonroad diesel fuel to 500 ppm.

Second, the cost study conservatively assumed that refiners would build their diesel desulfurization units 40 percent larger than their calendar day production volume. Our analysis assumed that the revamped or grassroots units would be sized 20 percent larger than the calendar day diesel fuel volume being desulfurized, and Mathpro assumed that the revamped and grassroots units would be sized 25 percent larger. Finally, the analysis did not attempt to estimate the likelihood and did not estimate the cost of nonhighway diesel

On a more fundamental level, we doubt that the perspective of whether to invest or not held by the surveyed refiners might have had earlier this year, or even now, will necessarily be the perspective that they will have several years from now when construction of the new units will have to begin. For example, many of these refiners haven't had the chance to test their diesel fuel to really understand what their cost would be for desulfurizing their highway diesel fuel. As the development of catalysts progresses which vendors expect to occur over the next two or so years,⁹ refiners may see that the difficulty and cost of meeting the cap standard is not as high as they once thought. Furthermore, these refiners would likely not make a firm decision on how they will invest at this point in time because they would need to better understand the plans of the rest of the refining industry. The temporary compliance option will give refiners insight on who will participate in the program and what their likely market share will be for distillate products. If refiners do not consider the intended actions of their fellow refiners, there is significant economic risk. Using this analysis as an example, if refiners invest in a way that would result in a shortfall of 12 percent in highway diesel fuel capacity, we estimate that there would be overproduction of nonroad diesel fuel by 20 percent. Those refiners which choose not to produce highway diesel fuel would see the price of nonroad diesel drop through the floor and their profits suffer accordingly. We do not believe that refiners would put themselves at that kind of risk.

Ensys for the Department of Energy

Ensys estimated the cost of desulfurizing highway diesel fuel for the Department of Energy (DOE). Ensys studied various levels of desulfurization, however, we will discuss the case which estimated the cost of averaging 8 ppm, which is about the level of sulfur control needed to meet the 15 ppm cap standard. Ensys only studied the cost of meeting the highway diesel fuel sulfur requirement in PADD 3. EnSys did not estimate how many refiners would

⁹ Two vendors have announced higher activity desulfurization catalysts since the point in time that the CRI survey was completed.

build new desulfurization units and how many would modify their current hydrotreaters, but presented costs for doing either. Thus, the lower limits of the ranges shown in Table V.C-24 assume refiners will modify their current hydrotreaters, while the upper limits assume that refiners would build new units. EnSys also projected costs for two separate sets of technologies. One set was considered conservative and relied upon technology that is already in commercial use. EnSys' costs using the conservative technology are higher than our estimates. This is due to the fact that this technology involves greater capital investment and greater consumption of hydrogen, because this technology is not just designed to reduce sulfur, but to reduce aromatic content, increase cetane levels and perform some cracking. The second technology analyzed by EnSys was labeled as optimistic. We believe the technology assumed to be used in the optimistic case was similar to that projected to be used by EPA (as well as CRA and Mathpro) since EnSys developed these costs after we shared vendor information with EnSys. EnSys reported their costs based on a 10 percent after tax return on investment, however, in Table V.C-25 below, we adjusted the EnSys costs to a 7 percent ROI before taxes.

EnSys made the following estimates for sizing their diesel desulfurization units. Unit size based on calendar throughput was increased by 5 percent to account for unit downtime, then an additional 15 percent calendar to stream day factor was added on. Unit size was adjusted upward by another 15 percent as a "redundancy" factor to cover the processing of off-spec batches. The offsite battery limit capital costs for new units were 40 percent of the onsite battery limit costs, while revamp unit inside and offsite capital costs were 50 percent of new unit onsite and offsite costs. EnSys received comments on their modeling study by a refining industry consultant with Pricewaterhouse Coopers retained by the Association of Automobile Manufacturers. The consultant commented on a series of cost factors used in EnSys' refinery modeling study. EnSys estimated maintenance costs to be 3.5 percent of total capital costs, while the consultant explained that the maintenance cost typically is 2.5 - 3 percent of the refinery's replacement value. EnSys estimated taxes insurance and overhead to be 2% of total investment, while the refining industry typically experiences 0.5 to 0.7 percent for taxes and insurance. The consultant also recommended that three other factors, 3 percent for buildings, 7 percent for environmental and 10 percent for startup, be reduced by 50 percent.

Table V.C-25. Comparison of DOE and EPA Refining Costs for Meeting a 15 ppm Highway Diesel Fuel Sulfur Cap Standard (7% ROI before taxes)

	<i>DOE Conservative Technology</i>	<i>DOE Optimistic Technology</i>	<i>EPA</i>
Per-Gallon Cost (c/gal)	5.1 - 6.0 (5.3)	4.2 - 4.4 (4.2)	4.3
Capital Cost (\$MM)	3.9 - 6.5 (4.4)	2.7 - 4.5 (3.1)	5.3

Lower end of the range in per-gallon costs assumes 100 percent revamped equipment; upper end assumes all new equipment; EPA costs and DOE costs in parentheses assume 80 percent revamps and 20 percent new units. DOE costs are only for the Gulf Coast refining region, which have slightly lower per-gallon costs than the entire U.S., and about half the capital costs.

National Petroleum Council Study

At the request of the Secretary of Energy, the National Petroleum Council (NPC) studied the impact of various possible fuel programs on the industry’s capability to continue to produce and distribute refined products, and maintain the viability of its refineries. The fuel programs studied by the NPC include desulfurizing gasoline, desulfurizing diesel fuel, eliminating MTBE from gasoline, and reducing the driveability index of gasoline. To carry out the study, the NPC established a committee comprised primarily of representatives of the oil industry, but representatives of the pipeline companies, engineering contractors, the Department of Energy, and the EPA participated as well. An important part of the study was to estimate the cost of the fuel programs being studied. The NPC estimated the cost for desulfurizing diesel fuel to meet an average sulfur standard of 30 ppm. Since the NPC did not study the cost of a 15 ppm cap standard, we cannot compare the NPC costs with our costs. However, it would still be useful to summarize those costs to get some indication of how an NPC cost for 15 ppm would compare to ours.

The NPC did not fund its own refinery modeling work. Instead, NPC relied upon the EMA-funded Mathpro cost analysis as the basis for its cost analysis. NPC concluded that it does not believe that the Mathpro study adequately captured the costs of achieving the very low sulfur levels included in some of the Mathpro study cases. While NPC admits that it could not review the vendor submissions on which Mathpro based its analysis, nevertheless, NPC concluded that the vendor data used was optimistic about achieving very low sulfur levels treating typical feedstocks which are eventually blended into highway diesel fuel. Consistent with its conclusion that the Mathpro analysis was optimistic, the NPC made a number of adjustments to the Mathpro cost analysis to provide its own cost analysis. Capital investments were increased by 20 percent. However, how hydrogen consumption was handled was less clear as early on in the report, hydrogen consumption and other operating costs were increased by 15 percent, but later on in the report the study described the adjustment for hydrogen consumption to be 20 percent. Also, the report stated that the offsite factor for the diesel desulfurization units were reduced from 1.5 to

1.4. Thus, assuming that both adjustments applied, there was a net increase in the investment costs of 10 percent. Mathpro modeled various refiner investment strategies which included the construction of a new unit and a revamp with another reactor in series. To meet a 30 ppm average sulfur standard, NPC assumed that half of highway diesel fuel would be desulfurized by a revamped unit, while the other half would be desulfurized with a new unit. After making these adjustments, NPC estimated that desulfurizing highway diesel fuel down to 30 ppm on average would cost 5.8 c/gal with capital costs amortized at a 10 percent after tax rate of return.

We have several comments on NPC's diesel cost analysis. First, NPC applied cost adjustment factors to increase the Mathpro cost analysis without having seen the vendor submissions. Also NPC adjusted Mathpro's cost estimates based on its assertion that the vendor's costs are overly optimistic. Even if NPC's adjustments factors correctly account for overoptimism in the vendor's estimate, they don't consider expected reductions in operating costs, and perhaps even capital costs, likely to occur as diesel desulfurization technology improves over time. Second, the considerations voiced above concerning Mathpro's modeled source and cost of hydrogen still apply for the NPC costs as well. Finally, NPC assumed 50-50 mix for revamps and new units which seems conservative for a moderate decrease in sulfur. NPC's mix of revamp and new units is much more conservative than the Charles River and Baker and O'Brien analysis for API. The analysis for API assumed a 40-60 mix for revamps and new units, respectively, however, for meeting a much more stringent 15 ppm cap sulfur standard.

3. The Added Cost of Distributing Low-Sulfur Fuel

a. Summary

Please refer to section IV.D. in this RIA for a detailed discussion of the changes that will need to take place in the highway diesel fuel distribution system as a result of our program. This section addresses the costs of these changes. The majority of the increase in distribution costs to adequately limit sulfur contamination during the distribution of 15 ppm diesel fuel are associated with an increase in the volume of highway diesel fuel that must be downgraded to a lower value product during transport by pipeline. There are also substantial costs associated with the need for additional storage tanks to handle two grades of highway diesel fuel during the initial period of our sulfur program when two grades of highway diesel fuel are allowed to be sold (15 ppm and 500 ppm sulfur cap highway diesel fuels).

We estimate that as a result of our sulfur program, distribution costs will increase by 0.5 cents per gallon of highway diesel fuel supplied when the sulfur requirements are fully effective beginning in the year 2010. During the initial years of our sulfur program (2006 through mid-2010) we estimate that the increase in distribution costs will be 1.1 cents per gallon of highway diesel fuel supplied. This estimate includes 0.7 cents per gallon for new storage tanks to handle two grades of highway diesel fuel (500 ppm and 15 ppm) during the initial years. For the sake of simplicity and to allow a comparison with distribution costs once the sulfur program is fully

effective, the distribution costs during the initial years are also expressed in terms of the total volume of highway diesel fuel supplied. This includes 500 ppm as well as 15 ppm highway diesel fuel.

In the proposed rule, we estimated that distribution costs would increase by 0.2 cents per gallon if the proposed requirement that the entire highway diesel fuel pool meet a 15 ppm sulfur cap beginning in 2006 be adopted. This cost was comprised of roughly 0.1 cents per gallon due to an increased volume of highway diesel fuel downgraded to a lower value product during shipment by pipeline and additional terminal testing costs, and 0.1 cents per gallon for distributing the additional volume of highway diesel fuel needed due to an anticipated decrease in fuel energy density as a side effect of reducing the sulfur content to the proposed 15 ppm cap. The case evaluated in the Notice of Proposed Rulemaking (NPRM) is most similar to that for the fully effective sulfur program in the final rule.

We took advantage of additional information contained in the comments to the NPRM in formulating a more comprehensive estimate of the distribution costs for the final rule. In some cases this involved adjusting an estimate for a parameter that factored into our calculation of costs in the NPRM. One important example is that we increased our estimate of the additional volume of highway diesel shipped by pipeline that would need to be downgraded to a lower value product. This downgrade volume is primarily the result of mixing that occurs between highway diesel fuel and high sulfur products that are shipped in the pipeline adjacent to highway diesel fuel. This mixture is referred to as interface when it can be blended into another product and transmix when it must be returned to the refinery for reprocessing. In other cases, our reevaluation of distribution costs included the consideration of parameters that did not factor into the estimation of distribution costs in the proposed rule. For example, commenters to the NPRM brought to our attention that there would be additional costs associated with changes in the handling practices for interface volumes that result from shipments of highway diesel fuel and jet fuel or kerosene which abut each other in the pipeline. We also attributed some cost to account for the process of testing and optimizing the distribution system to limit sulfur contamination. This includes the cost for testing to evaluate potential sources of contamination, and for miscellaneous minor procedural and hardware changes that may be needed, but have yet to be identified.

There are a number of common factors in the estimation of distribution costs during the initial years of our program and after the sulfur requirements becomes fully effective, such as the increase in interface volumes for pipeline shipments of highway diesel fuel. However, there are other factors that are unique to the estimation of costs during the initial years of the program. The factors that cause distribution costs to differ during the period when both 15 ppm and 500 ppm fuels are available for highway use:

- Having a lesser volume of 15 ppm diesel fuel in the system during the initial years of the program reduces some of the direct costs associated with distributing 15 ppm fuel.

- Having an additional grade of highway diesel fuel in the system (500 ppm) during the initial years of our program creates additional pipeline interface volumes, and additional product downgrade costs. Having 500 ppm highway diesel fuel in the system during the initial years of our program also allows some opportunity for the pipeline interface volumes associated with the shipment of 15 ppm fuel and jet fuel or kerosene to be downgraded to 500 ppm diesel fuel rather than off highway diesel fuel. This will reduce the cost of making this downgrade.

- The need for additional storage tanks to handle an additional grade of highway diesel fuel when the optional compliance option program is available creates additional costs that must be accounted for during the initial years of our program.

Table V.C-26 on the following page presents a summary of the distribution costs during the initial years of our sulfur program and after the program becomes fully effective. The manner in which these costs were estimated is discussed in the following sections.

Table V.C-26. Distribution Costs During the Initial Years of Our Sulfur Program and After the Program Becomes Fully Effective

Cost Components	Distribution Costs (cents per gallon of all highway diesel fuel supplied) ^A	
	Fully Effective Sulfur Program (2010 and later)	Initial Period (2006 - 2010)
Cost to Distribute Additional Volume Needed to Compensate for Reduced Energy Density of 15 ppm Sulfur Highway Diesel Fuel	0.17	0.14
Cost to Downgrade Additional Volume of 15 ppm Sulfur Highway Diesel Fuel to a Lower Value Product During Transport by Pipeline	0.14	0.10
Increased Cost for the Current Volume of Highway Diesel Fuel that Must be Downgraded in the Pipeline System	0.09	0.08
Increased Cost to Downgrade the Interface Volume Between Pipeline Shipments of Highway Diesel Fuel and Jet Fuel or Kerosene to Off Highway Diesel Fuel	0.07	0.03
Cost of Increased Terminal Testing	0.002	0.002
Cost of Additional Tanks to Handle Pipeline Interface Between Shipments of Jet Fuel and 15 ppm Sulfur Highway Diesel Fuel	Completely amortized during the initial years of program	0.009
Cost to Downgrade the Interface Volumes Associated with Pipeline Shipments of 500 ppm Fuel During the Initial Years of Our Program	No Additional Cost	0.004
Cost of Additional Tanks at Refineries, Terminals, Bulk Plants, and Truck Stops to Handle Two Grades of Highway Diesel Fuel During the Initial Years of Our Program	Completely amortized during the initial years of program	0.7
Cost of Optimizing the Distribution System to Limit Sulfur Contamination ^B	0.025	0.027
Total	0.5	1.1

^A During the initial years of our program, "all highway diesel fuel" includes 500 ppm highway diesel fuel as well as 15 ppm highway diesel fuel.

^B Cost amortized over the first 15 years of our sulfur program (through 2020).

There were some instances where we recognized that the rule would cause some change to current industry practice, but we concluded that the associated costs would not be significant. In one such case, we acknowledged that tank-truck operators and other distributors of highway diesel fuel downstream of the pipeline may need to be more careful in their observance of current industry practices used to limit product contamination, but we estimated that this would not result in a significant increase in costs (see Section V.C.3.i.). In another such case, we recognized that the use of diesel fuel additives with a sulfur content above 15 ppm would likely be phased out gradually by marketplace forces resulting from our diesel sulfur program, but concluded that this would be accomplished without a significant burden (see Section V.C.3.j.).

Our response to the public comments on the NPRM related to the costs of our sulfur control program are contained in a separate Response to Comments (RTC) document.

b. Cost of Distributing the Additional Volume of Highway Diesel Fuel Needed to Compensate for a Reduction in Energy Density

The energy density of highway diesel fuel is expected to decrease as a side effect of reducing the sulfur content to meet the proposed 15 ppm cap. As a result of this reduction in energy density, an increased volume of diesel fuel will need to move through the distribution system to meet the same level of consumer demand. The cost of producing this additional volume is included in the calculation of refinery costs (see Section V.C.1.). The cost of distributing the additional volume of highway diesel fuel needed to compensate for the lower energy density of highway diesel fuel that meets a 15 ppm sulfur cap is estimated at 0.17 cents per gallon of highway diesel fuel supplied under the fully effective program. During the initial years of our program, this cost is estimated at 0.14 cents per gallon. This cost is 20 percent lower during the period when the temporary compliance option is available because approximately 80 percent of the highway diesel fuel pool is required to meet a 15 ppm sulfur cap during this period.^f

In the NPRM, we estimated that the cost of distributing highway diesel fuel was equal to the difference in price at the refinery rack and the retail price. For the final rule, we based our estimate of distribution cost on a PADD by PADD evaluation of the difference in the price of highway diesel fuel at the refiner rack versus the retail price. The price differential for each PADD was weighted by the additional volume of fuel we anticipate will need to be produced in each PADD to arrive at an estimate of distributing the additional volume needed for the nation as a whole. Table V.C-27 provides a summary of the PADD-based values used in this calculation.

^f See section V.C.3.k. in this RIA for a discussion of how the relative volumes of 15 ppm and 500 ppm highway diesel fuel vary over the period when the temporary compliance program is available.

Table V.C-27. Data Used to Calculate the Cost of Distributing the Additional Volume of Highway Diesel Fuel Needed to Compensate for a Reduction in Energy Density

PADD	Price at the Retail Pump ¹ (cents / gallon)	Price at the Refinery Rack ^A (cents per gallon)	Retail -Refinery Rack Price (cents per gallon)	Additional Volume Needed (fraction of supply) ^B
1	68.8	55.5	13.3	0.034
2	68.6	56.9	11.7	0.035
3	65.5	54.0	11.5	0.035
4	75.8	66.7	9.1	0.034
5	80.0	62.9	17.1	0.033
National Average	71.7	59.2	12.5	0.034

^A Average price, excluding taxes, over the five year period from 1995 - 1999. Energy Information Administration (EIA), Petroleum Supply Annual (PSA), 1995-1999. Five year average costs were used for the purpose of this calculation to provide an estimate of the typical difference between the price at the refinery rack and at the retail pump.

^B Based on our estimate of the changes refiners will make to meet the 15 ppm sulfur cap for highway diesel fuel. See Section IV.A.

We believe the approach outlined above provides a more accurate estimate of costs. Since the difference in price at the refiner rack versus that at retail also includes some profit for the distributor and retailer, its use provides a conservatively high estimate of distribution costs. The fact that a slightly less dense (lighter, less viscous) fuel would require slightly less energy to be distributed also indicates that this estimate is conservative.

c. Cost of Downgrading an Increased Volume of Highway Diesel Fuel to a Lower Value Product During Shipment by Pipeline

We estimated that the volume of highway diesel fuel that is currently downgraded to a lower value product during shipment by pipeline is 2.2 percent of the total volume of highway diesel fuel supplied and that this volume would double to 4.4 percent due to the implementation of our sulfur control program. Please see section IV.D.2.a. for a discussion of how we arrived at this estimate. This section addresses the cost of the additional downgrade volume (2.2 percent) caused by our sulfur program. The cost to produce this additional volume is discussed in section V.C.2.

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The cost of downgrading the increased volume of highway diesel fuel to a lower value product is based on the difference in the cost of 15 ppm sulfur diesel fuel and the product to which the interface is downgraded. When our program is fully effective, this downgrade will be made into the off highway diesel pool. The cost of this increased volume of downgrade when the program is fully effective is estimated at approximately 0.14 cents per gallon of highway diesel supplied under the fully effective program. The cost of this additional downgrade is somewhat less during the initial years of our sulfur program because of the ability to downgrade 40 percent of the additional downgrade volume to 500 ppm diesel fuel in those pipelines that we expect will carry 500 ppm diesel fuel^s. The cost of the additional downgrade during the initial years of our program is estimated at 0.1 cents per gallon of highway diesel fuel supplied.

Following is a discussion of how we arrived at the above estimates.

There are two factors which influence the cost of making the downgrade of highway diesel fuel discussed above. The first is the volume of the amount of highway diesel fuel that must be downgraded. The second is the cost of making the downgrade based on the difference between the cost of highway diesel fuel and the product that it is being downgraded to.

When our sulfur program is fully effective, the cost of downgrading the additional 2.2 percent of highway diesel fuel to a lower value product is the 6.5 cents / gallon difference in the cost of producing a gallon of 15 ppm highway diesel fuel and that of producing a gallon of off highway diesel fuel.¹ To derive an estimate of the cost of this additional downgrade in terms of the total volume of highway diesel fuel supplied, 6.5 cents / gallon was multiplied by the additional fraction of the highway diesel pool that will need to be downgraded (0.022) to arrive at result 0.14 cents per gallon.

During the initial years of our program, there will be a smaller additional volume of highway diesel fuel that must be downgraded to a lower value product because some of the highway diesel pool will continue to be 500 ppm fuel. We estimated that approximately 80 percent of the highway diesel pool will be 15 ppm fuel during the initial years of our program.^u This reduces the cost associated with the additional downgrade. The cost of the additional downgrade is also reduced during the initial years of our program because 40 percent can be downgraded to 500 ppm highway diesel fuel which is a higher value product than off highway diesel fuel. This is based on our estimate that 40 percent of the pipeline systems that carry

^s See section V.C.3.k. in this RIA for additional discussion regarding the extent to which we anticipate 500 ppm diesel fuel will be present in the distribution system..

¹ See section table V.C-20 and attending text in section V.C.2. for a discussion on the difference in the cost of producing 15 ppm highway diesel fuel and that of producing off highway diesel fuel.

^u See section V.C.3.k. for a discussion on the relative volumes of 15 ppm and 500 ppm highway diesel fuel during the initial years of our program .

highway diesel fuel will carry both 15 ppm and 500 ppm highway diesel fuel.^v We used our estimate of the cost of producing 15 ppm highway diesel fuel under the fully effective program relative to the cost to produce 500 ppm diesel fuel today (4.1 cents per gallon) in calculating the cost of downgrading 15 ppm highway diesel fuel to 500 ppm highway diesel fuel. This provides a conservatively high estimate, since production costs for 15 ppm are somewhat lower during the start up of the program.^w

Based on the above inputs, we estimate that the cost of the additional downgrade will be 0.11 cents per gallon for the 40 percent of fuel distributed using the part of the system that handles both grades of highway diesel fuel, and 0.08 cents per gallon for the 60 percent of fuel that is distributed using the part of the system that carries only 15 ppm highway diesel fuel. By weighting these two results, we arrived at our over-all estimate of the cost of the additional volume of highway diesel fuel that will be downgraded to a lower value product of 0.1 cents per gallon of highway diesel fuel supplied.

d. Increased Cost of Downgrading the Current Interface Volumes Associated with Pipeline Shipments of Highway Diesel Fuel

We identified that there would also be an increase in the economic impact for the existing volume of interface currently associated with pipeline shipments of highway diesel fuel. This is because the cost of downgrading the existing interface volume would be determined by the difference between the cost of 15 ppm sulfur fuel and off highway diesel fuel rather than the difference in cost between current 500 ppm diesel fuel and off highway diesel fuel as it is today. We estimate that the increase in the cost of downgrading the existing highway diesel interface would be 0.09 cents per gallon of highway diesel fuel supplied during the fully effective program. During the initial years of our program, we estimate this cost at 0.08 cents per gallon of highway diesel fuel supplied. Following is a discussion of how we arrived at these estimates.

When our sulfur program is fully effective, all of the volume of highway diesel fuel shipped by pipeline that must be downgraded to a lower value product must be downgraded to off highway diesel fuel. Therefore, the additional cost of downgrading the current volume of highway diesel fuel that must be downgraded will be based on the difference in the cost of producing 15 ppm highway diesel fuel and off highway diesel fuel (6.5 cents per gallon) compared to the current difference in cost between 500 ppm highway diesel fuel and off highway

^v See section V.C.3.k. regarding the extent that we expect the distribution system will carry 500 ppm highway diesel fuel during the initial years of our program when the temporary compliance option is available.

^w See table V.C-20 and the associated text in section V.C.2. for a discussion on the difference in the cost of producing 15 ppm highway diesel fuel and that of producing 500 ppm highway diesel fuel.

diesel fuel (2.2 cents per gallon).^x Our estimate of the additional cost (0.09 cents per gallon of highway diesel fuel supplied) after our sulfur program is fully effective was calculated by multiplying the 4.3 cents per gallon price differential by the fraction of the highway diesel pool that is currently downgraded to a lower value product (0.022).^y Costs during the initial years of our program are reduced by 20 percent at (to 0.08 cents per gallon of highway diesel fuel supplied) because on average only 80 percent of the highway diesel fuel pool will be 15 ppm fuel during the initial years of our program when the temporary compliance option is available.^z

e. Increased Cost of Downgrading the Interface Between Pipeline Shipments of Highway Diesel Fuel and Jet Fuel or Kerosene

Please refer to section IV.D.2.a in this RIA for a more thorough discussion of the change that will need to take place in the handling practices for the interface volumes between adjacent pipeline shipments of highway diesel fuel and jet fuel or kerosene. This section addresses our estimation of the costs of this change.

Expressed in terms of the volume of highway diesel fuel supplied, we estimate the increased cost of handling these interface volumes will be 0.07 cents per gallon after our becomes sulfur program fully effective. This cost arises from the fact that all of the interface volume between adjacent batches of highway diesel fuel and jet fuel or kerosene will need to be downgraded to off highway diesel fuel once our program becomes fully effective. During the initial years of our program, we estimate that the cost will be 0.03 cents per gallon. The costs is somewhat less during the initial years of our program because there is some opportunity to make the downgrade to 500 ppm highway diesel fuel rather than off highway diesel fuel. Additional storage tanks will be needed at those terminals that currently do not handle off highway diesel fuel. The cost of these tanks has been fully accounted for in the calculation of costs during the initial years of our program as discussed below (0.009 cents per gallon).

Since a clean interface cut is already made between batches of highway diesel fuel and jet fuel or kerosene, there will be no increase in the volume of product downgraded under our program. However, the entire interface volume between highway diesel fuel and jet fuel or kerosene will need to be directed into a storage tank containing off highway diesel fuel when the 15 ppm cap on the sulfur content of highway diesel fuel is implemented. The current practice is to cut all of the interface volume associated with adjacent batches of highway diesel fuel and jet

^x See table V.C-20 and the associated text in section V.C.2. for a discussion on the relative cost of producing these different types of diesel fuel.

^y See section IV.D.2. for a discussion in our estimation of the current downgrade volume.

^z See section V.C.3.k. for a discussion on the relative volumes of 15 ppm and 500 ppm highway diesel fuel during the initial years of our sulfur program.

fuel or kerosene into the batch of highway diesel fuel. When our sulfur program is fully effective, the increased cost associated with this downgrade will be based on the difference in cost between 500 ppm highway diesel fuel and off highway diesel fuel (2.2 cents per gallon). This is because the downgrade will be made to off highway diesel fuel rather than 500 ppm highway diesel fuel as it is today.

To account for the fact that not all batches of highway diesel fuel are shipped by pipeline adjacent to a batch of jet fuel, 2.2 cents per gallon was multiplied by the ratio of the volume of jet fuel and kerosene supplied to the volume of highway diesel fuel supplied (0.72). For the purpose of this calculation, we assumed that 72 percent of the highway diesel fuel batches shipped by pipeline about a shipment of jet fuel or kerosene. We derived the ratio of the volume of jet fuel and kerosene supplied to the volume of highway diesel fuel supplied using the following data from the Energy Information Administration (EIA):⁷⁹

- Jet Fuel and kerosene supplied in 1999 = 637,123,000 barrels = 26,759,166,000 gallons
- 500 ppm diesel supplied in 1999 = 887,355,000 barrels = 37,268,910,000 gallons
- (jet fuel + kerosene) / 500 ppm diesel = 0.72

To arrive at our estimate of the additional cost of the downgrade associated with batches of highway diesel fuel that about batches of jet fuel or kerosene during shipment by pipeline when our program is fully effective, we multiplied the volume of the downgrade by the difference between the cost of 500 ppm highway diesel fuel and off highway diesel fuel (2.2 cents per gallon).

During the initial years of our program, 40 percent of pipeline systems will carry both 500 ppm and 15 ppm highway diesel fuel. In such systems the downgrade can continue to be made to 500 ppm diesel fuel rather than off highway diesel fuel. Therefore, there will be no additional cost associated with this downgrade. Consequently, the additional cost of the downgrade is reduced by 40 percent during the initial years of our sulfur program (0.07×40 percent = 0.03 cents per gallon).

Following is a discussion of how we arrived at our estimate of 0.009 cents per gallon of highway diesel fuel produced for the storage tanks that will be needed to accommodate the interface between pipeline shipments of highway diesel fuel and jet fuel/kerosene at terminals that do not already have a storage tank that contains off highway diesel fuel. We estimated that approximately 60 percent of terminals will not have such a tank (588 terminals). At such terminals, we estimate that a single 4,000 gallon above ground tank will be installed at a cost of \$20,000 per tank. The total tank cost will be \$11,760,000. This cost was amortized (at 7 percent per annum) over the initial years of the sulfur program to arrive at our estimate of 0.009 cents per

gallon of highway diesel fuel supplied. We used our estimate of the total volume of highway diesel fuel supplied in 2006^{aa} (39,504,000,000 gallons) to arrive at this per gallon estimate.

f. Cost of Additional Quality Control Testing at Petroleum Terminals

The additional quality control testing at the terminal level needed to ensure compliance with the 15 ppm sulfur cap would be the same during the initial years of our program as after the requirements are fully implemented. We estimate the cost of such additional quality assurance measures will be \$100 for each batch. This estimate includes the cost of sampling and testing each batch for its sulfur content. A typical pipeline batch of highway diesel fuel shipped by pipeline is 100,000 barrels. By dividing the estimated cost per batch by the average size of a batch, we arrived at an estimate of 0.002 cents per gallon of highway diesel fuel supplied for the cost of the additional quality control measures needed at terminal facilities.

g. Cost of Downgrading the Additional Pipeline Interface Volumes Associated with the Shipment of Highway Diesel Fuel that Meets a 500 ppm Sulfur Cap During the Initial Years of Our Sulfur Program

The presence of two grades of highway diesel fuel (500 ppm and 15 ppm) during the initial years of our program will cause the generation of additional pipeline interface volumes and associated downgrade costs. This is because there will be more batches of highway diesel fuel shipped in the 40 percent of pipelines that carry both grades of highway diesel fuel.^{bb} We estimate the additional cost during the initial years of our program will be 0.004 cents per gallon of the total volume of highway diesel fuel supplied (500 and 15 ppm sulfur cap fuel).

We arrived at this estimate by multiplying the following factors:

- The volume of the downgrade associated with pipeline shipments of 500 ppm highway diesel fuel (2.2 percent)^{cc}

^{aa} The estimate of highway diesel fuel supplied in 2006 was derived by growing the estimate of highway diesel fuel supply in 1999 from the Energy Information Administration (EIA) Petroleum Supply Annual, June 2000, by 1.5 percent each year. See docket item IV-A-07 for a discussion of our use of the 1.5 percent growth factor.

^{bb} See section V.C.3.k. in this RIA regarding the extent that we expect the distribution system will carry 500 ppm highway diesel fuel during the period when the temporary compliance option is available.

^{cc} See section IV.D.2. in this RIA for a discussion of our estimate of the volume downgraded.

- The fraction of the highway diesel pool we expect to be 500 ppm fuel (approximately 20 percent during the initial years of our program)^{dd}
- The fraction of the pipeline system that will carry 500 ppm fuel (40 percent)^{ee}
- The cost of the downgrade (2.2 cents per gallon)

h. Cost of Optimizing the Distribution System to Distribute 15 ppm Highway Diesel Fuel

As more fully discussed in section IV.D, we expect that the distribution industry will conduct various tests to evaluate potential sources of contamination prior to the implementation of our sulfur control program. During this evaluation, we anticipate that minor procedural and equipment changes may be identified in addition to those which we have specifically assigned a cost to. Such additional changes may include:

- Testing the system to evaluate sources of contamination
- Valve replacements
- Moving pipeline batch monitoring systems upstream and/or speeding the means to make batch changes
- Education programs for tank truck, tank wagon, and rail car operators on practices to limit contamination

We believe that the costs associated with such optimization practices will be relatively minor and readily accommodated by the distribution industry. Such costs will only occur once and the associated situations will be the exception rather than the rule. Since commenters did not provide an estimate of the frequency when such instances might arise, it is difficult to estimate a cost. Based on engineering judgement, having reviewed the information in the comments and the potential cost for a range of potential activities, we estimate that the fuel distribution industry will invest another \$100,000,000 to optimize its ability to limit sulfur contamination in addition to the costs that we have specifically identified (e.g. downgrade, additional tanks). We estimate that this investment will be made almost entirely by pipeline and terminal operators. We amortized this cost at 7 percent per annum over the period from the program's start-up in 2006 through 2020. During the initial years of our program, this results in a cost of 0.027 cents per

^{dd} For the purpose of this calculation, we used 20 percent for the entire 4 year period when the temporary compliance option is available. See section V.C.3.k. in this RIA for a discussion of how the relative volumes of 15 ppm and 500 ppm highway diesel fuel vary over the period when the temporary compliance program is available. For example, during the first year of our sulfur program, we estimate that 22 percent of highway diesel fuel will meet a 500 ppm sulfur cap.

^{ee} See section V.C.3.k. in this RIA regarding the extent that we expect the distribution system will carry 500 ppm highway diesel fuel during the period when the temporary compliance option is available.

gallon of highway diesel fuel supplied. When our program is fully effective, we estimate the cost at 0.025 cents per gallon through the year 2020.

i. Additional Measures by Tank Truck, Tank Wagon, and Rail Car Operators to Limit Contamination

As discussed in the section on the feasibility of distributing 15 ppm highway diesel fuel (section IV.D.), we continue to believe that there will only be negligible costs to tank truck, tank wagon, and rail car operators associated with limiting contamination during the distribution of 15 ppm highway diesel fuel. Given the such potential cost would be very small, we believe they are sufficiently well accounted within the costs we have attributed to the optimization of the distribution system to limit contamination (V.C.3.h.).

j. Potential Costs Associated with the Voluntary Phase Out of High Sulfur Diesel Additives

As discussed in the section on the feasibility of distributing 15 ppm diesel fuel (section IV.D.), we believe that the allowance for the continued use of diesel fuel additives which exceed 15 ppm in sulfur content will prevent any significant cost impacts from our program related to the use of diesel fuel additives.

k. Costs During the Initial Years of Our Program Due to the Need for Additional Storage Tanks to Handle Two Grades of Highway Diesel Fuel

The most substantial additional costs associated with the temporary compliance option are due to the need to handle an additional grade of highway diesel fuel in the distribution system. During the initial years of our program when the temporary compliance option is available, we expect that the production of 500 ppm sulfur fuel will be much less than that of 15 ppm fuel. At the same time, most of the diesel vehicle fleet can burn 500 ppm fuel during this period. Because of its greater volume and the need to distribute it everywhere in the country, we expect that essentially all pipelines and terminals will handle 15 ppm fuel. In contrast, distribution of 500 ppm fuel will concentrate on those areas nearest the refineries producing that fuel, plus a few major pipelines serving major refining areas.

Regarding distribution to the final user, we expect that nearly all truck stops in areas where 500 ppm fuel is available will invest in piping and tankage to handle a second fuel. Because of the significant expense involved in adding a second tank, in these areas, we expect service stations will only carry one fuel or the other, as market demands dictate. Likewise, we expect that centrally fueled fleets and card locks will only handle 15 ppm fuel. Under this scenario, sales of 500 ppm fuel are limited to only those vehicles which refuel at truck stops and service stations. This is somewhat conservative since some centrally fueled fleets may have the flexibility to inexpensively handle two fuels. Likewise, some card locks in a given area may be

able to carry 15 ppm fuel and others 500 ppm fuel and still serve their clients at little extra cost. Still, given the above assumptions, we project that the 500 ppm fuel will have to be distributed to areas representing about 50% of the national diesel fuel demand. Also, as the fleet turns over to 2007 and later vehicles, the amount of 500 ppm fuel produced under the temporary compliance option will gradually decrease from roughly 22 percent in 2007 to about 16 percent in 2010.

The tankage cost at refineries, terminals, pipelines and bulk plants handling both fuels is estimated to be \$0.81 billion. We estimate that 11 refineries will produce both fuels. These are refineries with hydrocrackers which are not projected to invest in new hydrotreating equipment in 2006. Thus, these refineries will produce a small amount of 15 ppm fuel from its hydrocrackate and 500 ppm fuel from the rest of its current highway diesel fuel blendstocks. At \$1 million per tank, this totals to \$11 million.

We estimate that there are 853 terminals which currently carry highway diesel fuel, excluding tanks at refineries. We assume that 40% of these terminals would build a new tank in order to distribute two fuels to 50% of the U.S. market and keep tank truck driving distances at current levels. We estimate only 40% of these terminals would need an extra tank, rather than 50%, because 56 refineries will be producing the 500 ppm fuel and will distribute this fuel directly to their local areas. At a cost of \$1 million per tank, terminal tankage will cost a total of \$340 million.

Likewise, we estimate that there are 9200 bulk plants which currently carry highway diesel fuel, excluding tanks at refineries. We estimate that a new tank at these facilities would cost \$125,000. Again assuming that 40% of these bulk plants would build a new tank in order to distribute two fuels to 50% of the U.S. market, this tankage would cost a total of \$460 million.

Finally, we estimate that 50% of the nation's truck stops would also build a new tank or otherwise provide for a second fuel. There are 4800 truck stops currently operating in the U.S.⁸⁰ The National Association of Truck Stop Operators (NATSO) surveyed their members regarding the expected cost to handle a second grade of highway diesel fuel.⁸¹ We weighted the responses to this survey to arrive at our estimate that it would cost \$100,000 per truck stop on average to handle a second fuel. This totals to \$240 million. Thus, the total cost for new tankage at all of these facilities is \$1.05 billion.

We then amortized these one time costs over the 15 ppm fuel produced during the initial years of our program at 7 percent per annum. We estimated that, with the small refiner option, the total percentage of 15 ppm fuel produced during the first year of our program would be 78% (though it could be as low as 75% if all small refiners chose to delay production of 15 ppm fuel). This continued through 2008. However, in 2008, the limitation of distributing 500 ppm fuel only through truck stops and service stations and only in 70% of the U.S. diesel fuel market, as well as the turnover of the vehicle fleet to 2007 and later vehicles, began to be controlling. We estimate that truck stops and service stations distribute 61% of all highway diesel fuel in the U.S. We

assumed that these outlets sold 15 ppm and 500 ppm in proportion to the in-use vehicle fleet (i.e., 2007 and later vehicles used 15 ppm fuel and earlier vehicles used 500 ppm fuel). Thus, in 2009 and 2010, we estimated that 81%, and 83.5% of all highway diesel fuel would meet the 15 ppm standard. The last figure was assumed to apply through mid- 2010, based on the use of banked credits from earlier periods. Amortizing the tankage cost over the 15 ppm fuel produced over this period, the cost per gallon is 0.9 cents.

4. What is the Cost of Lubricity Additives?

Adoption of the cap on diesel fuel sulfur could result in a decrease in the lubricity of highway diesel fuel produced by some refiners. This could necessitate the use of additional quantities of lubricity-improver additives to maintain in-use lubricity performance (see Section IV.C.).

A study by MathPro Inc. (MathPro)⁸² in 1999, sponsored by the Engine Manufacturers Association to estimate the costs of diesel fuel desulfurization under sulfur standards that we were likely to require, received estimates from lubricity additive suppliers indicating that the costs of lubricity additives would average 0.1 to 0.5 cents per gallon. The lower the sulfur standard, typically the higher the lubricity cost. We independently contacted some producers and distributors of lubricity additives, which also provided estimated average costs in the range of 0.1 to 0.5 cents per gallon for large volumes of treated fuel. Again, the estimates varied depending on the sulfur standard, ranging from a cap of 5 to 50 ppm. MathPro utilized vendor cost estimates to derive lubricity additive cost estimates under a number of possible diesel fuel sulfur control scenarios. These estimates ranged from 0.1 to 0.3 cents per gallon depending on the control case (see Table V.C-28).

Table V.C-28. MathPro Lubricity Additive Cost Estimates

<i>Sulfur Control Case (avg. sulfur standard)</i>		<i>Estimated Lubricity Additive Cost (cents/gallon)</i>
<i>Highway Diesel</i>	<i>Off Highway Diesel</i>	
150 ppm	uncontrolled (3500 ppm)	0.1
150 ppm	150 ppm	0.1
50 ppm	50 ppm	0.1
20 ppm	350 ppm	0.1
20 ppm	20 ppm	0.2
2 ppm	350 ppm	0.2
2 ppm	2 ppm	0.3

Unfortunately, MathPro did not provide costs for a case consistent with the 15 ppm sulfur standard. In addition, MathPro cases included control of off highway diesel fuel. Nevertheless, the cases evaluated in the MathPro study can be used to approximate the cost of lubricity additives under the 15 ppm cap for highway diesel fuel. Of the cases evaluated by MathPro, we believe its highway/off-highway 20 ppm average scenario most closely matches our highway-only 15 ppm cap case with respect to the potential impact on lubricity additive cost. While our projected refinery average sulfur level of 7 ppm is closer to 2 ppm than 20 ppm, we believe that Mathpro's 2 ppm case, which includes the desulfurization of both highway and non-highway diesel fuel to this level, is much more severe with respect to lubricity changes than a 7 ppm level for highway diesel fuel only. Thus, using the vendor-supplied cost estimates, coupled with the estimates for the various scenarios evaluated by MathPro, we estimate that the cost of lubricity additives under the 15 ppm sulfur cap would be in the range of 0.2 cents per gallon.

In considering the comments, we have found no basis in today's action to use a different average cost estimate to treat low sulfur diesel fuel for lubricity than that which was used in the proposal. Of the two comments we received on this issue, one supported our cost estimate of 0.2 cents per gallon. The other was submitted by DOD, which indicated it has experienced lubricity additive costs from one to five cents per gallon. We believe that DOD's experience with lubricity properties and lubricity additives is not typical of commercial users for several reasons. First, DOD commented that, due to harsher operating conditions, engines used in DOD vehicles, especially tactical vehicles, are more vulnerable to lubricity problems than the same engines operated in commercial vehicles. Also, the fuel DOD uses at its facilities is purchased under

contract usually for a year or longer. Thus, the DOD fuel generally is from a single supplier and does not have the beneficial effect of blending or mixing different batches of fuel or fuel from different suppliers, such as that which occurs in the commercial market. As discussed in Section IV, blending or mixing different batches of diesel fuel minimizes the effect of isolated poor lubricity fuels. Consequently, DOD might be taking more aggressive action in responding to lubricity concerns than might be needed for commercial applications. Second, DOD is using an additive that is primarily a corrosion inhibitor. It is our understanding that DOD found that the additive it uses to address a corrosion property in the fuel is also effective at improving lubricity, and subsequently has been using that additive to also address its lubricity concerns. If DOD were able to ignore its corrosion property concerns, it is possible that a formulation specifically for lubricity might cost less, or that its treat rate could be less, than that of the corrosion inhibitor formulation and treat rate it currently uses. Finally and most importantly, we believe that DOD's experience is more reflective of the prices that might be experienced with specialty additives supplied in relatively small quantities. With the 15 ppm standard, most, if not all, of the nation's highway diesel fuel may need to be treated for lubricity. Economies of scale associated with bulk production as opposed to more specialty products will drive down the unit cost of lubricity additives considerably.

5. Benefits of 15 ppm Diesel Fuel for the New and Existing Diesel Fleet

In addition to its role as a technology enabler, low sulfur diesel fuel gives benefits in the form of reduced sulfur induced corrosion of vehicle components and slower acidification of engine lubricating oil, leading to longer maintenance intervals and lower maintenance costs. These benefits will apply to new vehicles and to the existing heavy-duty vehicle fleet beginning in 2006 when the fuel is introduced. These benefits can offer significant cost savings to the vehicle owner without the need for purchasing any new technologies. These benefits are estimated here for new vehicles and for vehicles in the existing fleet (pre-2007 fleet).

The individual components of the engine system which might be expected to realize benefits from the use of low sulfur diesel fuel are summarized in Table V.C-29 and are described in more detail in the following sections.

Table V.C-29. Components Potentially Affected by Lower Sulfur Levels in Diesel Fuel

<i>Affected Components</i>	<i>Affect of Lower Sulfur</i>	<i>Potential Impact on Engine System</i>
Piston Rings	Reduce corrosion wear	Extended engine life and less frequent rebuilds
Cylinder Liners	Reduce corrosion wear	Extended engine life and less frequent rebuilds
Oil Quality	Reduce deposits and less need for alkaline additives	Reduce wear on piston ring and cylinder liner and less frequent oil changes
Exhaust System (tailpipe)	Reduces corrosion wear	Less frequent part replacement
EGR	Reduces corrosion wear	Less frequent part replacement

The actual value of these benefits over the life of the vehicle will depend upon the length of time that the vehicle operates on low-sulfur diesel fuel. For a vehicle near the end of its life in 2007 the benefits will be quite small. However for vehicles produced in the years immediately preceding the introduction of low-sulfur fuel the savings will be substantial. These savings are estimated here for new and existing diesel vehicles beginning in 2006 and continuing through 2035. The costs are expressed in terms of dollars saved per mile or in terms of dollars saved in a particular year (for rebuild savings).

These savings, due to the use of low sulfur diesel fuel, can also be expressed in terms of a savings in cents per gallon of low sulfur diesel fuel. Taking the savings detailed in each of the subsections below and expressing them in terms of cents per gallon gives an average savings of approximately 1.4 cents/gallon for light heavy-duty diesels, 1 cent/gallon for medium heavy-duty diesel engines and 0.7 cents/gallon for heavy heavy-duty diesel engines. The average savings estimated across all weight classes is therefore approximately one cent per gallon. While there may be uncertainty regarding the magnitude of this effect, this estimate may in fact be a conservative estimate of the savings as there are likely to be other benefits not accounted for in this analysis.

a. Methodology

Under contract from EPA, ICF Consulting provided surveys to nine engine manufacturers seeking their input on expectations for cost savings which might be enabled through the use of

low sulfur diesel fuel and seeking their estimations of the cost and types of emission control technologies which might be applied with low sulfur diesel fuel. In general, the respondents to the survey gave qualitative rather than precise quantitative estimates of the benefits of low sulfur diesel fuel. While all respondents agreed that savings will occur, their estimates were often based on rough approximations of future engine characteristics. Based on responses to this survey, EPA estimated cost savings to the current and future fleets through the use of low sulfur diesel fuel.⁸³

For new vehicles we have estimated the value of these benefits in terms of a net present value in the year of vehicle sale. This allows for us to calculate a per vehicle cost of control and a per vehicle cost effectiveness for the program. In order to calculate aggregate benefits for the new fleet and for the existing fleet this approach is not appropriate as each vehicle in the fleet will accrue benefits at different rates over different periods, depending upon their year of introduction and their technology mix. Additionally, it is more telling to describe the cost savings as an aggregate benefit to the fleet, just as fuel costs are shown as an aggregate cost to the fleet. Therefore, where possible, we have estimated the benefits of low sulfur diesel fuel to the new and existing heavy-duty vehicle fleets in terms of dollars per vehicle mile traveled. In the one case, where the savings are related to a discrete event (engine rebuilds), we have applied a single savings estimated to a specific fraction of the existing fleet as described below. These savings are then accumulated over the entire pre-2007 heavy-duty fleet and over the new fleet of vehicles introduced in 2007 in each year from 2006 through 2035, and are reported as an aggregate savings.

If refiners avail themselves of the temporary compliance option and hardship provisions available to them in the early years of the program, some fraction of the existing fleet would continue to operate on current 500 ppm sulfur diesel fuel. In order to account for this possibility in our analysis, we have assumed that 22 percent of the total fuel consumption during the transition period will be today's 500 ppm sulfur fuel. The analysis also assumes that the new vehicles will be fueled exclusively on the new low sulfur diesel fuel and that only the fraction of the existing fleet operating on the remaining fraction of the low sulfur diesel fuel will realize a benefit.

b. Extended Oil Change Intervals

Sulfur in diesel fuel leads to acidification of engine lubricating oils, directly causing increased corrosion and increased rates of engine wear. Lubricating oils use alkaline additives to neutralize the acidifying nature of sulfur compounds formed in the engine from sulfur in diesel fuel. These basic compounds are consumed over time leading to a loss of pH control in the oil. Oil change intervals are often determined based upon the period of time required for the basic compounds in the oil to be consumed. The use of low sulfur diesel fuel will decrease this rate of oil acidification leading to extended periods between required oil change maintenance intervals. While it is difficult to quantify a precise benefit, most observers agree that use of very low sulfur

fuel will probably extend oil drain intervals. Based on information from some engine manufacturers and others, we have assumed that engine oil change intervals will be extended by ten percent due to the use of low sulfur diesel fuel. Based on this benefit the per mile savings can be estimated as shown in Table V.C-30.

Table V.C-30. Cost Savings to the Existing Fleet from Extend Oil Change Intervals Made Possible by Low Sulfur Diesel Fuel

	<i>Units</i>	<i>LHD</i>	<i>MHD</i>	<i>HHD</i>
Base Oil Change Interval*	miles	8,000	11,000	18,000
Low Sulfur Oil Change Interval*	miles	8,800	12,100	19,800
Cost Per Oil Change*	\$	\$100	\$150	\$200
Base Oil Change Cost per Mile	\$/mile	\$0.0125	\$0.0136	\$0.0111
Low Sulfur Oil Change Cost per Mile	\$/mile	\$0.0114	\$0.0124	\$0.0101
Oil Change Cost Difference per Mile	\$/mile	\$0.0011	\$0.0012	\$0.0010
Average Fuel Economy	miles/gallon	11.8	8.0	5.9
Cost Savings Per Gallon Fuel	\$/gallon	\$0.0134	\$0.0099	\$0.0060

*Oil change intervals for vehicles operating on low sulfur diesel fuel are assumed to increase by ten percent, average oil change intervals, and costs for oil changes from ICF Consulting report.⁸⁴

For vehicles produced after the introduction of the low sulfur diesel fuel in 2006 these benefits can also be expressed in terms of an average cost savings over the life of the vehicle. The cost savings are estimated using typical mileage accumulation rates given in each year of a vehicles life from our inventory emissions model and the typical oil change interval and costs described above. These savings are then expressed in terms of a net present value in the year of the vehicle sale. The savings realized for extended oil change intervals on vehicles fueled exclusively on low sulfur diesel fuel are estimated to be \$153 for light heavy-duty vehicles, \$249 for medium heavy-duty vehicles and \$559 for heavy heavy-duty vehicles.

c. Extended EGR System Life

In the RIA for the 2004 heavy-duty engine standards, we estimated that exhaust gas recirculation (EGR) systems, particularly EGR valves, will require service or replacement as part of the engine rebuild process. This estimate was based primarily upon our concern for the

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detrimental effects of sulfur in diesel fuel on EGR system durability. The use of low sulfur diesel fuel mitigates this concern and leads us to conclude that the EGR valve used in these systems can be expected to last the life of the engine. Eliminating the replacement of the EGR valve on heavy heavy-duty diesel engines represents a cost savings to vehicles built with EGR systems of \$115 in the year of the engine rebuild. These savings are only estimated for vehicles built after 2004, because vehicles built prior to that date will have operated primarily on current high sulfur diesel fuel. Savings for light and medium heavy duty vehicles are not estimated because engines in these vehicle classes are less likely to be rebuilt. The analysis also assumes that vehicles with EGR systems will be operated primarily on the new low sulfur diesel fuel when it becomes available in 2006. Although some fraction of the existing fleet may be operating on high sulfur diesel fuel during that period, we believe that owners of vehicles with EGR systems will preferentially choose the low sulfur diesel fuel for the maintenance benefits it provides. The aggregate savings for vehicles sold in 2004-2006 and rebuilt in 2009-2011 are shown in Table V.C-31. The aggregate savings for vehicles built beginning in 2007 and rebuilt beginning in 2012 are presented in Table V.C-32. These savings can also be expressed in terms of a net present value in the year of vehicle sale of \$51.

Table V.C-31. Cost Savings to the Existing Fleet for Reduced EGR System Replacement Made Possible by Low Sulfur Diesel Fuel*

<i>Year Rebuilt (7th year of life)</i>	<i>Model Year</i>	<i>Calendar Yr Sales</i>	<i>Surviving in Year 7</i>	<i>Number Rebuilt</i>	<i>Aggregate Savings</i>
2010	2004	259,600	185,874	176,580	\$20,306,691
2011	2005	264,000	189,024	179,573	\$20,650,872
2012	2006	268,400	192,174	182,566	\$20,995,053

* \$115 per vehicle cost savings if the EGR valve is not replaced when the engine rebuild occurs. The table assumes that only Heavy Heavy-Duty engines are rebuilt, that 95 percent of vehicles reaching 560,000 miles are rebuilt, and that 72 percent of heavy heavy-duty vehicles reach 560,000 miles (on average in year 7 of their life).

Table V.C-32. Cost Savings to the New Fleet (2007 and later) for Reduced EGR System Replacement Made Possible by Low Sulfur Diesel Fuel*

<i>Year Rebuilt (7th year of life)</i>	<i>Model Year</i>	<i>Calendar Yr Sales</i>	<i>Surviving in Year 7</i>	<i>Number Rebuilt</i>	<i>Aggregate Savings</i>
2013	2007	272,800	195,325	185,559	\$21,339,234
2014	2008	277,200	198,475	188,551	\$21,683,416
2015	2009	281,600	201,625	191,543	\$22,027,598
2016	2010	286,000	204,775	194,535	\$22,371,780
2017	2011	290,400	207,925	197,527	\$22,715,962
2018	2012	294,800	211,075	200,519	\$23,060,144
2019	2013	299,200	214,225	203,511	\$23,404,326
2020	2014	303,600	217,375	206,503	\$23,748,508
2021	2015	308,000	220,525	209,495	\$24,092,690
2022	2016	312,400	223,675	212,487	\$24,436,872
2023	2017	316,800	226,825	215,479	\$24,781,054
2024	2018	321,200	229,975	218,471	\$25,125,236
2025	2019	325,600	233,125	221,463	\$25,469,418
2026	2020	330,000	236,275	224,455	\$25,813,600
2027	2021	334,400	239,425	227,447	\$26,157,782
2028	2022	338,800	242,575	230,439	\$26,501,964
2029	2023	343,200	245,725	233,431	\$26,846,146
2030	2024	347,600	248,875	236,423	\$27,190,328
2031	2025	352,000	252,025	239,415	\$27,534,510
2032	2026	356,400	255,175	242,407	\$27,878,692
2033	2027	360,800	258,325	245,399	\$28,222,874
2034	2028	365,200	261,475	248,391	\$28,567,056
2035	2029	369,600	264,625	251,383	\$28,911,238

* \$115 per vehicle cost savings if the EGR valve is not replaced when the engine rebuild occurs. The table assumes that only Heavy Heavy-Duty engines are rebuilt, that 95 percent of vehicles reaching 560,000 miles are rebuilt, and that 72 percent of heavy heavy-duty vehicles reach 560,000 miles (on average in year 7 of their life).

d. Extended Exhaust System Life

Exhaust system components, specifically exhaust pipes and mufflers, typically fail due to perforations caused by corrosion of the pipe walls. Corrosion rates are increased by sulfuric acid present in diesel exhaust which can condense on the walls of the exhaust system. This sulfuric acid is a by-product of combustion with sulfur in diesel fuel. When sulfur is removed from diesel fuel the amount of sulfuric acid formed decreases proportionally, thereby reducing corrosion rates due to sulfuric acid in diesel exhaust. The survey respondents acknowledged that this may be a cost savings to the consumer, but were not able to quantify the savings or determine the percent extended life. One manufacturer characterized the savings as marginal. Based on this information, we have assumed that the reduction in sulfuric acid induced corrosion may extend exhaust system component life by five percent, leading to a cost savings to the existing vehicle fleet. Based on this estimate and estimates of average exhaust system life and average exhaust system replacement costs, a per mile estimate of this cost savings can be determined as shown in Table V.C-33. We have not applied this savings to estimates for the new vehicle fleet because we do not anticipate the use of a muffler on vehicles equipped with diesel PM filters.

Table V.C-33. Cost Savings to the Existing Fleet from Extend Exhaust System Replacement Intervals Made Possible by Low Sulfur Diesel Fuel

	<i>Units</i>	<i>LHD</i>	<i>MHD</i>	<i>HHD</i>
Exhaust System Change Interval	miles	110,000	147,000	334,000
Low Sulfur Exhaust Change Interval*	miles	115,500	154,350	350,700
Exhaust Replacement Cost	\$	\$275	\$379	\$491
Base Cost per Mile	\$/mile	\$0.0025	\$0.0026	\$0.0015
Low Sulfur Cost per Mile	\$/mile	\$0.0024	\$0.0025	\$0.0014
Cost Difference Per Mile	\$/mile	\$0.0001	\$0.0001	\$0.0001
Average Fuel Economy	miles/gallon	11.8	8.0	5.9
Cost Savings Per Gallon Fuel	\$/gallon	\$0.0014	\$0.0010	\$0.0004

* Exhaust system life for vehicles operating on low sulfur diesel fuel are expected to increase by 5 percent.⁸⁵

e. Extended Rebuild Intervals and Engine Life

Engine rebuilds and replacements often occur when excessive wear of the engine cylinder kit (primarily the cylinder liner and engine piston rings) causes high oil consumption rates, decreased engine performance and increased fuel consumption rates. Wear rates of these components can increase due to corrosion caused by sulfur in diesel fuel. Therefore, in as much as low sulfur diesel fuel can be expected to decrease corrosion, it can also be expected to similarly decrease component wear rates, thereby leading to increased component life. Extending engine life or the time between engine rebuilds, can lead to a direct savings to the consumer.

Estimating an average extension of engine life is difficult due to the many factors that affect engine wear and overall engine life. We believe the strong influence of sulfur in diesel fuel on engine wear could lead to estimates of about five percent. However, because engine wear rates are also linked to oil change intervals it may not be appropriate to claim full credit for both extended oil change intervals and extended engine rebuild intervals. Therefore, in order to be conservative in our estimates, we have not included these cost savings in our estimates of aggregate cost savings realized through the use of low sulfur diesel fuel.

f. Aggregate Cost Savings for the New and Existing Diesel Fleet Realized from Low Sulfur Diesel Fuel

By applying the cost savings described in the preceding sections to the predicted vehicle miles traveled for each class of heavy-duty vehicle in the inventory calculation model described in chapter 2 of this RIA, an estimated aggregate savings can be calculated. These savings are shown for the fraction of the existing fleet (pre-2007 vehicles) operating on the new low sulfur diesel fuel in Table V.C-34 beginning with the savings realized in 2006 from the introduction of low sulfur diesel fuel in that year. As vehicles in the pre-2007 fleet are retired from service these cost savings decrease as reflected in the table.

Aggregate savings for vehicles introduced beginning in 2007 are estimated in the same manner except that they are assumed to always be operated on the required low sulfur diesel fuel and are presented in Table V.C-35. As the number of new vehicles in the fleet increases the total savings realized through the use of low sulfur diesel fuel increases in proportion as seen in the table.

Table V.C-34. Aggregate Savings to the Existing Fleet (pre-2007 fleet) Made Possible by Low Sulfur Diesel Fuel

<i>Calendar Year</i>	<i>Aggregate Savings</i>
2006	\$80,431,146
2007	\$220,884,072
2008	\$182,897,940
2009	\$149,160,147
2010	\$150,798,213
2011	\$134,706,583
2012	\$120,588,873
2013	\$86,874,251
2014	\$75,690,690
2015	\$65,859,406
2016	\$63,293,317
2017	\$73,979,411
2018	\$64,024,039
2019	\$55,275,661
2020	\$47,592,312
2021	\$40,856,134
2022	\$34,971,949
2023	\$29,858,909
2024	\$25,419,320
2025	\$21,528,956
2026	\$18,117,665
2027	\$15,124,047
2028	\$12,494,644
2029	\$10,182,634
2030	\$8,147,249
2031	\$6,307,402
2032	\$4,685,085
2033	\$3,334,379
2034	\$2,061,983
2035	\$949,181

Table V.C-35. Aggregate Savings for the New Fleet (2007 and later) Made Possible by Low Sulfur Diesel Fuel

<i>Calendar Year</i>	<i>Aggregate Savings</i>
2006	\$0
2007	\$24,971,224
2008	\$66,505,419
2009	\$104,161,427
2010	\$138,377,022
2011	\$169,546,107
2012	\$198,021,885
2013	\$245,459,554
2014	\$269,806,304
2015	\$292,307,844
2016	\$313,186,610
2017	\$332,638,971
2018	\$350,838,377
2019	\$367,935,864
2020	\$384,061,052
2021	\$399,321,575
2022	\$413,804,401
2023	\$427,583,405
2024	\$440,747,742
2025	\$453,410,634
2026	\$465,636,121
2027	\$477,480,251
2028	\$488,991,818
2029	\$500,213,568
2030	\$511,182,712
2031	\$521,973,234
2032	\$532,565,116
2033	\$542,908,991
2034	\$553,181,391
2035	\$563,308,011

6. Per-Engine Life-Cycle Fuel Costs

The additional cost of diesel fuel meeting our 15 ppm cap is encountered by the average engine owner each time the fuel tank is refilled. The impacts of the diesel sulfur standard on the average engine owner can therefore be calculated as the increased fuel costs in cents per gallon, multiplied by the total number of gallons used by an engine over a particular timeframe. Thus we have calculated the in-use impact of our diesel sulfur standard on a per-engine basis for both a single year and for an engine's entire lifetime.

Since we have introduced a temporary compliance option and small refiner hardship provisions for the diesel sulfur standard that will apply in the initial years, both 15 ppm highway fuel and 500 ppm highway fuel will be present in the distribution system at the same time during these years. As discussed in Section V.C above, there are both refinery cost savings and distribution system costs that occur as a result of these provisions. It is appropriate to consider these costs and savings as applying to the entire highway diesel pool. In order for refiners to continue producing 500 ppm fuel, we anticipate that they will have to purchase credits from refiners producing 15 ppm fuel, in essence raising the cost of producing 500 ppm fuel and lowering the cost of producing 15 ppm fuel. Furthermore the distribution system costs are likely to be recouped by the industry across both grades of highway diesel fuel. As a result, we have concluded that the fuel costs associated with the program we are finalizing today should be assigned equally to all gallons of highway diesel fuel, whether 15 ppm or 500 ppm sulfur fuel.

The total cost of 15 ppm diesel fuel is the sum of refinery desulfurization costs, addition of a lubricity additive, and increases in distribution costs. Refinery desulfurization and distribution costs are discussed earlier in this Chapter, and average 3.3 ¢/gal and 1.1 ¢/gal respectively during the initial years of the program. Lubricity additives are discussed in Section V.C.4, and average approximately 0.2 ¢/gal. Thus we estimate the total cost of diesel fuel meeting our 15 ppm cap to be 4.5 ¢/gal during the initial years of the program. This cost will increase to 5.0 ¢/gal after 2010.

In a single year, the average in-use heavy-duty engine travels approximately 30,000 miles^{ff}, though the mileage of any given engine varies by usage, age, and other factors. Applying the average heavy-duty fuel economy, the cost for 15 ppm diesel fuel of 4.5 ¢/gal leads us to a per-engine estimate of approximately \$187. This is the additional cost that the average engine owner will incur for fuel in the first year of our program, if the full social costs of meeting our standards are passed onto consumers. However, fuel prices may be higher or lower depending on market conditions. The costs for different engine classes will vary, of course, based on their respective annual mileages and fuel economies.

^{ff} Calculated from the annual miles traveled per heavy-duty engine for each year of a engine's life, multiplied by a distribution of engine registrations by year. Estimate of 30,000 miles per year includes all HD weight classes and urban buses.

The per-engine cost of 15 ppm diesel fuel can also be calculated over the lifetime of a engine. However, to calculate a lifetime cost for the average in-use engine, it is necessary to account for the fact that individual engines experience different lifetimes in terms of years that they remain operational. This distribution of lifetimes is the engine survival rate distribution, for which we used registration data from an Arcadis report. The costs of 15 ppm diesel fuel incurred over the lifetime of the average fleet engine can then be calculated as the sum of the costs in individual years as shown in the equation below:

$$LFC = \sum [(AVMT)_i \cdot (SURVIVE)_i \cdot (C) \div (FE)]$$

Where:

- LFC = Lifetime fuel costs in \$/engine
- (AVMT)_i = Annual engine miles travelled in year i of a engine's operational life⁸⁶
- (SURVIVE)_i = Fraction of engines still operating after i years of service⁸⁷
- C = Cost of 15 ppm diesel fuel, \$0.045/gal in 2006 and \$0.050/gal in 2011
- FE = Fuel economy in miles per gallon (Appendix VI-A)
- i = Engine years of operation, counting from 1 to 30

We used the above equation to calculate lifetime fuel costs separately for LH, MH, HH, and urban buses. We also weighted the per-engine costs for the individual engine classes by their contribution to sales. The results are shown in Table V.C-36 as "undiscounted lifetime costs."

An alternative approach to calculating lifetime per-engine costs of 15 ppm diesel fuel is to discount future year costs. This approach leads to "net present value" lifetime fuel costs, and is a useful means for showing what the average engine owner would have to spend in the first year in order to pay for all future year fuel costs. It also provides a means for comparing the program's costs to its emission reductions in a cost-effectiveness analysis, as described in Chapter VI.

Discounted lifetime fuel costs are calculated in an analogous manner to the undiscounted values, except that each year of the summation is discounted at the average rate of 7 percent. The equation given above can be modified to include this annual discount factor:

$$LFC = \sum [\{ (AVMT)_i \cdot (SURVIVE)_i \cdot (C) \div (FE) \} / (1.07)^{i-1}]$$

Once again, we used the above equation to calculate discounted lifetime fuel costs separately for LH, MH, HH, and urban buses, then weighted the per-engine costs for the individual engine classes by their contribution to sales. The results are shown in Table V.C-36 as "discounted lifetime costs."

Table V.C-36. Fleet Average Per-Engine Lifecycle Costs Of Diesel Fuel (\$)

	<i>LH</i>	<i>MH</i>	<i>HH</i>	<i>UB</i>	<i>All</i>
First year	58	110	390	428	187
Undiscounted lifetime, near-term	801	1497	5395	7426	2583
Undiscounted lifetime, long-term	837	1565	5654	7629	2703
Discounted lifetime, near-term	576	1077	3969	4772	1881
Discounted lifetime, long-term	609	1141	4209	4959	1993

LH = Light heavy duty, MH = Medium heavy duty, HH = Heavy heavy duty,
 UB = Urban buses, All = Consumption weighted average of all engine weight classes

D. Combined Total Annual Nationwide Costs

Figure V.D-1 and Table V.D-1 summarize EPA's estimates of total annual costs to the nation for heavy-duty diesel engines, heavy-duty gasoline vehicles, and 15 ppm diesel fuel. The capital costs have been amortized for these analyses. The actual capital investment would occur up-front, prior to and during the initial years of the program, as described previously in this Chapter. The fuel costs shown are for all 15 ppm diesel fuel consumed nationwide, including that consumed in both highway and off-highway applications. Annual aggregate costs change as our new standards are phased-in and projected per-vehicle costs and annual sales change over time. The aggregate fuel costs change due to the temporary compliance option which applies between 2006 and 2010, and as annual fuel consumption changes over time as predicted by the Energy Information Administration. The methodology we used to derive the aggregate costs are described in detail in the previous Sections of this chapter. As shown below, total annual costs increase over the period of the temporary compliance option and peak at about \$3.6 billion in 2010. Total annualized costs are projected to increase gradually after 2010 due to projected growth in vehicle sales and fuel consumption.

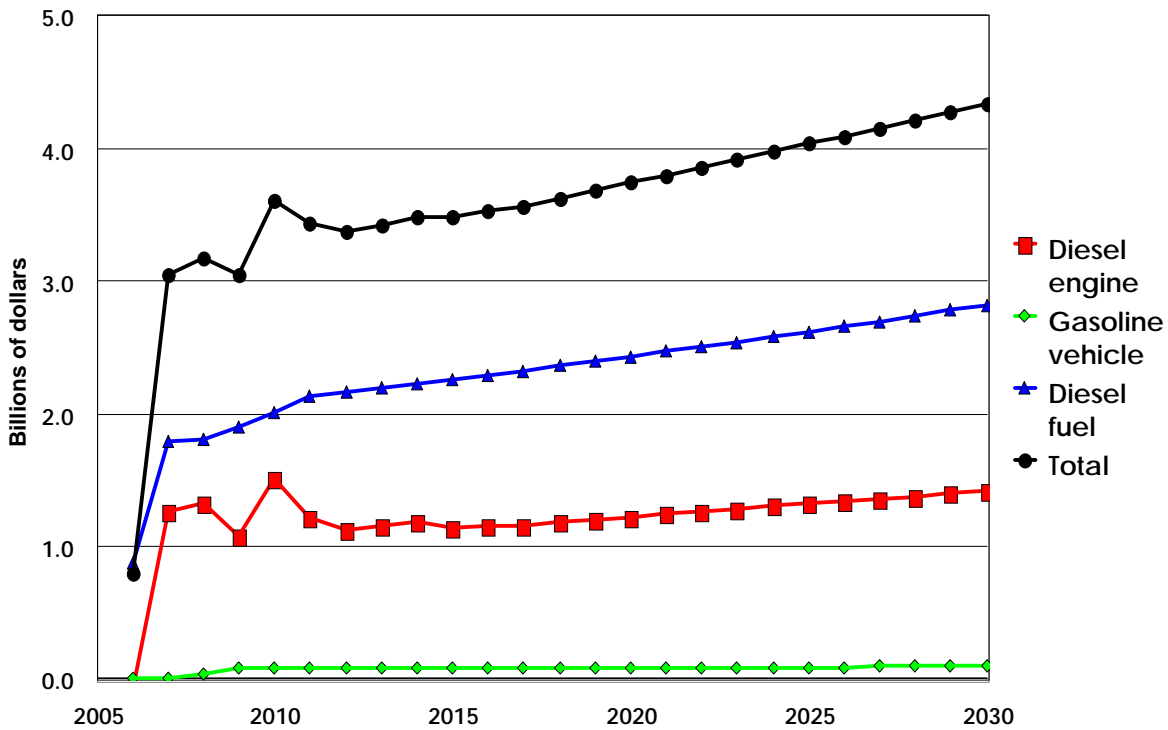


Figure V.D-1. Total annualized costs of heavy-duty diesel engines, heavy-duty gasoline vehicles, and 15 ppm diesel fuel

In Figure V.D-1, aggregate engine costs exhibit notable drops in years 2009 and 2011. The drop in year 2009 is due to the onset of the “learning curve” in the third year of the engine manufacturer’s production of engines meeting our new standards. In year 2010, the NOx phase-in ends and the remaining 50 percent of new engines must meet the new standards. This change causes a sudden increase in aggregate costs in 2010. In year 2011, a learning curve adjustment is again made and costs drop once again. Finally, in 2012 the fixed costs expire and the costs drop one last time. Thereafter, costs continue to increase due to growth in the fleet.

Table V.D-1. Total annualized costs of heavy-duty diesel engines, heavy-duty gasoline vehicles, and 15 ppm diesel fuel (\$million)

	<i>Diesel engines</i>	<i>Gasoline vehicles</i>	<i>Diesel fuel</i>	<i>Total</i>
2006	(80)	0	880	799
2007	1,266	0	1,786	3,052
2008	1,321	46	1,809	3,177
2009	1,072	80	1,904	3,056
2010	1,520	81	2,014	3,615
2011	1,225	82	2,128	3,434
2012	1,133	83	2,160	3,376
2013	1,157	78	2,192	3,427
2014	1,180	79	2,225	3,484
2015	1,141	80	2,258	3,480
2016	1,156	82	2,292	3,530
2017	1,159	83	2,327	3,568
2018	1,182	84	2,362	3,628
2019	1,205	85	2,397	3,687
2020	1,226	86	2,433	3,746
2021	1,247	87	2,469	3,804
2022	1,268	89	2,506	3,863
2023	1,288	90	2,544	3,921
2024	1,307	91	2,582	3,980
2025	1,326	92	2,621	4,039
2026	1,344	93	2,660	4,098
2027	1,362	94	2,700	4,157
2028	1,380	95	2,741	4,217
2029	1,398	97	2,782	4,276
2030	1,415	98	2,824	4,337

In support of the this rulemaking, the Agency is preparing both a benefit-cost analysis (BCA) and a cost-effectiveness analysis. The BCA presents and compares the social benefits (e.g., avoided adverse health effects) and social costs (e.g., direct compliance expenditures) of the program. Since many of the benefits and costs are manifest in future years, we apply discounting methods to adjust the dollar values of these effects to reflect the finding that society

as a whole typically values the realization (or avoidance) of a given effect differently depending on when the effect occurs. Because the BCA reflects the value of benefits and costs from the perspective of society as a whole, we use a 3 percent rate to discount future year effects in our primary analysis. The 3 percent rate is in the 2 to 3 percent range recommended by the Science Advisory Board's Environmental Economics Advisory Committee for use in EPA social benefit-cost analyses, a recommendation incorporated in EPA's new *Guidelines for Preparing Economic Analyses (November 2000)*. OMB Circular A-94 requires us to generate benefit and cost estimates reflecting a 7 percent rate, and results based on OMB's preferred 7 percent rate are also presented to demonstrate the sensitivity of our results to the discount rate assumption.

The BCA focuses on calendar year 2030 in its comparison of costs and benefits. The 2030 total program cost shown in Table V.D-1 above was based on a discount rate of 7 percent. Since the BCA requires a 2030 cost which based on a 3 percent discount rate, we developed this separately. Thus the total program cost in calendar year 2030 using a discount rate of 3 percent is \$4.2 billion. Note that since the discount rate only affects the return on capital investments in any given calendar year, and since all engine and vehicle capital investments have been recovered by 2030, the only effect of the discount rate in year 2030 is for fuel costs. As a result, the total program cost under the 3 percent assumption is very close to that under a 7 percent assumption.

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Chapter VI: Cost-Effectiveness

This Chapter will present the cost-effectiveness analysis we completed for our new heavy-duty gasoline vehicle, heavy-duty diesel engine, and diesel fuel sulfur standards. Under Clean Air Act Section 202(a)(3), we are required to promulgate standards which reflect the greatest degree of emission reduction achievable, giving appropriate consideration to cost, energy, and safety factors. The standards we set are not premised on the need to promulgate the most cost-effective standards. However, we have determined that cost-effectiveness is a useful tool in evaluating the appropriateness of our standards.

The cost-effectiveness analysis described in this Section relies in part on cost information from Chapter V and emissions information from Chapter II to estimate the dollars per ton of emission reductions produced from our standards. We have calculated the cost effectiveness using two different approaches, a per-vehicle approach that considers the costs incurred and emission reductions produced for a single vehicle or engine, and a 30-year net present value approach that accounts for all costs and emission reductions over a 30 year period beginning in 2006. The comparative merits and drawbacks of both approaches are described in Sections VI.A and VI.E. Finally, this Chapter compares the cost-effectiveness of the new provisions with the cost-effectiveness of other control strategies from previous and potential future EPA programs.

Sections VI.A, VI.B and VI.C describe the per-vehicle calculations for our combined heavy-duty diesel engine and diesel fuel sulfur standards, while Section VI.D describes the per-vehicle calculations for heavy-duty gasoline vehicles. Section VI.E describes the 30-year net present value cost effectiveness analysis. The results of all cost-effectiveness calculations are given in Section VI.F. Comments we received in response to our Notice of Proposed Rulemaking on the subject of cost effectiveness, along with our responses to those comments, can be found in Issue 5.9 of the Response To Comments document.

A. Overview of the Per-vehicle Analysis

The per-vehicle cost-effectiveness analysis conducted for our standards focused on the costs and emission reductions associated with a single engine (or vehicle, in the case of heavy-duty gasoline vehicle standards) meeting the 2007 model year standards, and operating on low sulfur fuel. Both costs and emission reductions were calculated over the life of the engine and then discounted at a rate of seven percent. Costs and emission reductions were measured relative to a baseline consisting of the 2004 certification standards and average diesel sulfur levels falling under the current 500 ppm cap. The calculations were performed separately for each engine class and the results weighted according to the expected fleet mix. Details on the per-vehicle approach

to cost-effectiveness follow. The presentation of the 30-year net present value cost effectiveness calculations can be found in Section VI.E. This latter approach includes the fuels costs incurred by the pre-2007MY fleet which are not accounted for in the per-vehicle analysis. Note that many of the issues discussed in this Section VI.A also apply to the calculation of 30-year net present value cost-effectiveness.

1. Temporal and Geographic Applicability

Our per-engine approach to our cost-effectiveness calculations produces \$/ton values representing any controlled engine, no matter where that engine operates. In effect, this means that emission reductions in both attainment and nonattainment areas are included in our cost-effectiveness analysis. The same holds true for our 30-year net present value analysis. Although this may limit the usefulness of comparisons to stationary source controls, we believe that our approach is appropriate. Both the engine and diesel sulfur programs are to apply nationwide, so the same emission reductions will occur regardless of where the engine operates. Attainment area emission reductions also produce health benefits. In general, the benefits of NMHC reductions in ozone attainment areas include reductions in emissions of air toxics, reductions in the contribution from NMHC emissions to the formation of fine particulate matter, and reductions in damage to agricultural crops, forests, and ecosystems from ozone exposure. Emission reductions in attainment areas help to maintain clean air as the economy grows and new pollution sources come into existence. Also, ozone health benefits can result from reductions in attainment areas, although the most certain health effects from ozone exposure below the NAAQS appear to be both transient and reversible. The closure letter from the Clean Air Science Advisory Committee (CASAC) for the recent review of the ozone NAAQS states that there is no apparent threshold for biological responses to ozone exposure.¹

In the Regulatory Impact Analysis for a recent rulemaking for highway heavy-duty diesel engine standards,² EPA also presented a regional ozone control cost-effectiveness analysis in which the total life-cycle cost was divided by the discounted lifetime NO_x + NMHC emission reductions adjusted for the fraction of emissions that occur in the regions expected to impact ozone levels in ozone nonattainment areas. (Air quality modeling indicates that these regions include all of the states that border on the Mississippi River, all of the states east of the Mississippi River, Texas, California, and any remaining ozone nonattainment areas west of the Mississippi River not already included.) The results of that analysis show that the regional cost-effectiveness values were 13 percent higher than the nationwide cost-effectiveness values. Because of the small difference between the two results, EPA is presenting only nationwide cost-effectiveness results for this analysis.

Despite the fact that a per-engine approach to cost-effectiveness allows us to avoid the arbitrary choice of a specific year in which to conduct the analysis, there is some value in examining different points in time after the program is first implemented. The costs of the

program will be higher immediately after it is implemented than they will be after several years, since engine and vehicle manufacturers can take advantage of decreasing capital and operating costs over time, and will learn how to produce their products more efficiently as time goes on. For the purposes of this rulemaking, therefore, we will present cost-effectiveness of our program on both a near-term and long-term basis. More details concerning per-engine costs are given in Section VI.B.2 for diesel engines and in Section VI.D.1 for heavy-duty gasoline vehicles.

We are also proposing that our combined engine/sulfur program (hereafter, this includes our standards for heavy-duty diesel engines, heavy-duty gasoline vehicles, and diesel sulfur) be an annual program. Since cost-effectiveness only has relevance when compared to alternative strategies, we must use an approach to calculating the cost-effectiveness of our annual program that is consistent with the approaches taken for other rulemakings. For programs that generate emission reductions outside of the ozone season, we generally include those "winter season" reductions in the cost-effectiveness calculations. Thus our cost-effectiveness estimates will include all the emission reductions produced as a result of our standards, no matter where or when those reductions occur. This is consistent with the methodology used in prior rulemakings and allows for an apples-to-apples comparison.

2. Baselines

There are two broad approaches to cost-effectiveness that can be taken, each of which requires a different baseline. These two approaches can be termed "incremental" and "average." Both incremental and average approaches to cost-effectiveness provide a measure of how much more stringent than the existing standards our standards can be before they cease to be cost-effective.

An incremental approach to cost-effectiveness requires that we evaluate a number of different potential standards, each of which is compared to the potential standards closest to it. Using this approach, the cost-effectiveness of our standards would be calculated with respect to another set of potential standards which is less stringent than our standards. In this way, the \$/ton values represent the last increment of control, highlighting any nonlinearities that exist in either the costs or emission reductions.

An average approach to cost-effectiveness, on the other hand, requires that we compare the costs and emission reductions associated with our standards to those for the previous set of standards that are being met by manufacturers. In this case, the \$/ton values represent the full range of control from the last applicable standard to our standards.

As stated above, we must use an approach to cost-effectiveness that is consistent with the approach taken in other rulemakings in order to provide an apples-to-apples comparison. Most other mobile source rulemakings use average cost-effectiveness, including our recently

promulgated standards for Tier 2 vehicles and gasoline sulfur. Therefore, we have chosen to calculate cost-effectiveness on an average rather than an incremental basis for our standards.

Since today's program includes both fuel standards and engine standards, it was necessary for us to define a baseline for both fuels and engines. For highway diesel fuel, the previous standard was set in 1990, limiting the sulfur content to a maximum of 500 ppm starting in 1993. However, the average sulfur level has been significantly less than 500 ppm, closer to 340 ppm.³ Therefore we have determined that the sulfur baseline should be 340 ppm.

For heavy-duty diesel engines, the previous set of standards was originally set in 1997 and applies to the 2004 model year.¹ These standards included a 2.4 g/bhp-hr cap for NO_x+NMHC or 2.5 g/bhp-hr with a 0.5 g/bhp-hr cap on NMHC. For the purposes of analysis we have assumed that manufacturers will meet this standard with 2.3 g/bhp-hr NO_x and 0.2 g/bhp-hr NMHC. However, unlike the PM standards we are proposing today, 2004 model year urban buses are required to meet a different PM standard (0.05 g/bhp-hr) than other heavy-duty engines (0.1 g/bhp-hr). Thus we have used two different baselines for PM, one for urban buses and another for other heavy-duty engines. Despite this, we are calculating only a single set of cost-effectiveness values for all engines since we are proposing that a single set of standards apply to urban buses and other heavy-duty engines.

For heavy-duty gasoline vehicles, the previous set of standards applies to the 2005 model year. For incompletes, these include a 1.0 g/bhp-hr NO_x+NMHC standard, which we assume separates practically into a 0.8 g/bhp-hr standard for NO_x and a 0.2 g/bhp-hr standard for NMHC. For Class 2b completes, the 2005 standards include 0.9 g/mile for NO_x and 0.28 g/mile for NMHC. Finally, for Class 3 completes, the 2005 standards include 1.0 g/mi for NO_x and 0.33 g/mi for NMHC.

B. Diesel Costs

The costs used in our cost-effectiveness calculations are the sum of the added costs of compliance with the 2007 engine and diesel sulfur standards on a per-engine basis, in comparison to the engine and fuel baselines. Costs result from discounting over the lifetime of an engine at a seven percent discount rate. In addition, all costs represent the fleet-weighted average of all light, medium, and heavy-heavy engines, as well as urban buses.

^a Under a consent decree, many manufacturers will be complying with these heavy-duty standards as early as 2002. Standards were finalized in the Federal Register at 65 FR 59896, October 6, 2000.

1. Near and Long-Term Cost Accounting

Since the costs of complying with the 2007 engine standards will vary over time, we believe that it is appropriate to consider both near-term and long-term costs in our cost-effectiveness analysis. First, the capital costs associated with the manufacture of engines that will meet the 2007 standards would generally be amortized over five years. Thus in the sixth year of production, a portion of the capital costs become zero and the total costs of production drop. Manufacturers also gain knowledge about the best way to meet new standards as time goes on (the so-called "learning curve"), and as a result their operating costs decrease over time. The implications of this learning curve on engine costs is discussed in Section V.A.1.

Thus near-term costs represent the highest costs of the program, as they include all capital costs and no cost savings due to the manufacturer's learning curve. Long-term costs, on the other hand, represent the lowest costs of the program which occur after a portion of capital cost amortizations have ended and all learning curve cost savings have been accounted for. For the purposes of this rulemaking, therefore, we will present cost-effectiveness of our program on both a near-term and long-term basis. Details about the calculation of near and long-term engine costs can be found in Section V.A.

2. Diesel Engine and Fuel Costs

The per-engine costs used in our cost-effectiveness calculations were derived and presented in Section V.A. Engine hardware costs were presented in Section V.A for the four engine categories affected by our standards. For the purposes of calculating cost-effectiveness, we weighted the costs for those four individual engine categories by the expected fleet fractions (see Table VI.C-2 below) to obtain fleet-average costs for our emissions standards. Also, we treated first-year production costs as the "near-term" costs, and sixth-year production costs as the "long-term" costs. For low sulfur diesel, we used the discounted lifetime costs presented in Table V.C-36 which include costs for desulfurization, lubricity additives, and distribution costs. The costs used in our cost-effectiveness calculations are shown in Table VI.B-1.

Table VI.B-1. Fleet-average, Per-engine Costs for HDDE

	<i>NOx adsorber, PM trap, and oxy catalyst (\$)</i>	<i>Fuel cost (\$)</i>	<i>Total costs (\$)</i>
Near-term	2457	1881	4338
Long-term	1332	1993	3325

Note that the total costs in Table VI.B-1 were used for establishing "uncredited" cost-effectiveness values. As described in Section VI.B.4, the costs from Table VI.B-1 were also adjusted to produce "credited" cost-effectiveness values.

3. Methodology for assigning costs to NO_x, NMHC, and PM

The object of our cost-effectiveness analysis is to compare the costs to the emission reductions in an effort to assess the program's efficiency in helping to attain and maintain the NAAQS. Thus the primary purpose of our standards is to reduce emissions of the ozone precursors hydrocarbons and oxides of nitrogen, as well as emissions of particulate matter. Therefore, consistent with our approach in previous rulemakings such as the recently finalized standards for Tier 2 vehicles and gasoline sulfur, we have calculated cost-effectiveness on the basis of total NO_x + NMHC emissions.

However, since we are also proposing that a new standard be set for PM, we must develop a separate cost-effectiveness value for that pollutant. We do not think it appropriate to combine NO_x, NMHC, and PM all into a single cost-effectiveness value, since there are separate NAAQS for ozone and PM, and these two pollutants do not have identical effects on human health and the environment. We must therefore determine a reasonable way to split the costs of compliance with our combined engine/diesel sulfur program between NO_x+NMHC and PM.

As described in Section III.A and in our Draft RIA, we expect that manufacturers will use both NO_x adsorbers and PM traps to comply with our engine standards. However, since publication of the NPRM we have determined that NMHC emissions may not be sufficiently controlled by the NO_x adsorber without the use of a clean-up oxidation catalyst downstream of the adsorber. See Section III.A.4 for a more detailed discussion of this issue. The NO_x adsorber and oxidation catalyst will together enable heavy-duty diesel engines to meet our new NO_x and NMHC standards. As a result, we believe that the total hardware costs associated with the NO_x adsorber and oxidation catalyst should be applied to the calculation of NO_x+HC cost-effectiveness. The PM trap will continue to provide reductions in both PM and HC as well as pre-conditioning the engine-out exhaust stream for introduction to the NO_x adsorber. As a result, for the purposes of calculating cost-effectiveness, we believe that the hardware costs of the PM trap should be divided equally between PM and NO_x+HC, consistent with the approach taken in the NPRM.

In order to divide the fuel costs appropriately between NO_x+HC and PM, we have taken an approach consistent with that described in the Draft RIA. The diesel fuel sulfur cap of 15 ppm has been implemented in order to enable the two aftertreatment components of PM trap and NO_x adsorber (+ oxidation catalyst) to operate properly. Since the fuel sulfur standard applies equally to both components of the aftertreatment, we believe it is appropriate to divide fuel costs evenly between the PM trap and the NO_x adsorber (+ oxidation catalyst).

However, as described above, the PM trap will continue to provide reductions in both PM and HC, pre-conditioning the engine-out exhaust stream for introduction to the NO_x adsorber. We therefore believe it is appropriate to divide the fuel costs applicable to the trap, calculated as half of total fuel costs, equally between PM and HC. As a result, 25 percent of total fuel costs would apply to the calculation of PM cost effectiveness, while the remaining 75 percent would apply to the calculation of cost effectiveness for NO_x+NMHC. Likewise, half of the hardware costs for the PM trap would be included in the calculation of cost effectiveness for NO_x+NMHC. This approach is consistent with that taken in the NPRM

4. Cost Crediting for SO₂

The reduction in diesel sulfur levels that would result from our standards will necessarily result in reductions in sulfur-containing compounds that exit the engine. These compounds are limited to sulfur dioxide (SO₂) and sulfate particulate matter. The latter will be taken into account as manufacturers seek to comply with our new PM standard, and thus will be automatically represented in our cost-effectiveness estimates of \$/ton PM. However, there is no engine standard for SO₂. Since reductions in emissions of SO₂ are beneficial and represent a true value of our program, we believe it is appropriate to account for them in our cost-effectiveness analysis.

The primary benefit of reductions in SO₂ emissions is a reduction in secondary PM, formed when SO₂ reacts with water and ammonia in the atmosphere to form ammonium sulfate. Therefore, we believe that any crediting for reductions in SO₂ should be applied to our PM costs.

To account for reductions in emissions of SO₂ in our cost-effectiveness calculations, we have calculated a second set of \$/ton values in which we credit some of the costs to SO₂, with the remaining costs being used to calculate \$/ton PM. As a result, we have produced both "credited" and "uncredited" \$/ton PM values; the former takes into account the SO₂ emission reductions associated with our standards, while the latter does not.

Cost-effectiveness values for the control of SO₂ represent conservative estimates of the cost of measures that would need to be implemented in the future in order for all areas to reach attainment. Such cost-effectiveness values are therefore an appropriate source for estimating the amount of the costs to credit to SO₂. As a result, we credited some costs to SO₂ through the application of cost-effectiveness (\$/ton) values for this pollutant drawn from other sources.

In concept, we would consider the most expensive program needed to reach attainment to be a good representation of the ultimate value of SO₂. However, in this rulemaking, we chose to simplify by using more conservative approaches to establish crediting values for SO₂. The potential future programs evaluated as part of the NAAQS revisions rulemaking (discussed in more detail in Section VI.F below) provided a reasonable source for identifying the value of SO₂

in terms of its cost-effectiveness. In this process we did not make a distinction between SO₂ emissions from mobile or stationary sources since there is little data to suggest that a tons of SO₂ from one source contributes differently to PM or acid rain problems than a ton of SO₂ from another source.

Out of the nine SO₂ control programs evaluated in the NAAQS revisions rule, eight were actually used in the modeling of ambient concentrations of PM based on their contribution to secondary PM (sulfate) levels in PM nonattainment areas. The cost-effectiveness of the eight SO₂ control programs ranged from \$1600/ton to \$111,500/ton. In this particular rulemaking, we have for simplicity's sake used the average cost effectiveness of the eight SO₂ control programs, calculated to be \$4800 a ton. This average value of \$4800/ton was used in the crediting of some costs to SO₂, and represents a conservative valuation of SO₂.

The cost crediting was applied after all costs associated with compliance with our standards were calculated and summed. The per-engine tons reduced of SO₂ was multiplied by the representative cost-effectiveness value of \$4800/ton (see Section VI.C.2 below for SO₂ tons calculations). As a result, \$446 of the total costs were apportioned to SO₂ in the calculation of PM cost-effectiveness. This amount is independent of whether we are considering a near-term or long-term cost-effectiveness calculation, since the lifetime tons reduced for this compound is the same, on a per-engine basis, in any year of the program. A summary of the costs used in our cost-effectiveness calculations is given below in Table VI.B-2, including all engine, fuel, and fuel economy costs.

Table VI.B-2. Fleet Average Per-Engine Costs for HDDE Used in Cost-effectiveness

	<i>Near-term costs (\$)</i>		<i>Long-term costs (\$)</i>	
	NO _x +NMHC	PM	NO _x +NMHC	PM
Total uncredited costs	3381	956	2563	762
SO ₂ credit allocation	n/a	-446	n/a	-446
Total credited costs	3381	510	2563	316

C. Emission Reductions from Diesel Engines

In order to determine the overall cost-effectiveness of the standards we are proposing, it was necessary to calculate the lifetime tons of each pollutant reduced on a per engine basis. This section will describe the steps involved in these calculations. In general, emission reductions

were calculated for NO_x, NMHC, PM, and SO₂ in a manner analogous to the discounted lifetime fuel costs described in Section V.C.6.

1. NO_x, NMHC, and PM

The discounted lifetime tonnage numbers for NO_x, NMHC, and PM for our combined diesel engine and diesel fuel standards were based on the difference between emissions produced by engines meeting our 2004 and 2007 standards, as described in Section II.B.1. These in-use emission levels were expressed in terms of average g/bhp-hr emissions for each year in a engine's life, up to 30 years. From this basis, lifetime tonnage estimates were developed using the following procedure:

- 1) Annual mileage accumulation levels for MOBILE6 were applied to the in-use emission rates for each year in a engine's life to generate total mass emissions produced in each year by that engine (this step included the use of bhp-hr/mile conversion factors)
- 2) The resultant mass emissions were multiplied by the probability of survival in the appropriate year, known as the "survival" rate.
- 3) A seven percent annual discount factor, compounded from the first year of the engine's life, was then applied for each year to allow calculation of net present value lifetime emissions.

Converting to tons and summing across all years results in the total discounted lifetime per-engine tons. This calculation can be described mathematically as follows:

$$LE = \sum [\{ (AVMT)_i \cdot (SURVIVE)_i \cdot (ER)_i \cdot (CF) \cdot (K) \} / (1.07)^{i-1}]$$

Where:

- LE = Discounted lifetime emissions in tons/engine
- (AVMT)_i = Annual miles traveled in year i of a engine's operational life⁴
- (SURVIVE)_i = Probability of engine survival after i years of service
- (ER)_i = Emission rate, g/bhp-hr in year i of an engine's operational life
- CF = Heavy-duty engine conversion factor, bhp-hr/mile (see Appendix VI-A)
- K = Mass conversion factor, 1.102 x 10⁻⁶ tons/gram
- i = Engine years of operation, counting from 1 to 30

For NO_x, NMHC, and PM, we generated discounted lifetime tonnage values for each engine class (LH, MH, HH, and urban buses) using the above equation. This was done separately for the baseline and control cases. The baseline case included the 2004 model year

engine standards and the in-use diesel sulfur level of 340 ppm. The control case entailed our 2007 model year engines standards and 7 ppm diesel sulfur. The tonnage values that we calculated according to this procedure are shown in Table VI.C-1.

Table VI.C-1. Per-engine Discounted Lifetime Tons for HDDE

	<i>NO_x</i>	<i>NMHC</i>	<i>PM</i>
<u>Baseline</u>			
LH	0.409	0.037	0.017
MH	0.970	0.086	0.041
HH	3.661	0.325	0.157
Urban bus	4.300	0.174	0.097
<u>Control</u>			
LH	0.035	0.025	0.001
MH	0.084	0.059	0.002
HH	0.320	0.224	0.009
Urban bus	0.357	0.155	0.010

The final step before calculating the cost-effectiveness of our program was to weight the discounted lifetime tonnage values for each engine class by their respective fraction of the HDDE fleet. These fractions were based on engine count projections for use in MOBILE6 for the year 2020 for diesel-powered heavy-duty engines (see Appendix VI-A), which in turn were based on current sales fractions for new vehicles. Table VI.C-2 presents the final weighting factors we used to develop fleet-average tonnage values.

Table VI.C-2. Engine Class Sales Weighting Factors for HDDE

Light-heavy duty	0.342
Medium-heavy duty	0.323
Heavy-heavy duty	0.326
Urban buses	0.009

The final discounted lifetime tonnage values for an average fleet engine meeting either the 2004 or 2007 standards are shown in Table VI.C-3. It is these values that were used directly in calculating the cost-effectiveness of our program.

Table VI.C-3. Fleet average, Per-engine Discounted Lifetime Tons for HDDE

	NO _x + NMHC	PM
Baseline: 2004 standards with 340 ppm fuel	1.8329	0.07117
Control: 2007 standards with 7 ppm fuel	0.2490	0.00399
Reduction	1.5839	0.06718

2. Sulfur Dioxide

The sulfur contained in diesel fuel exits the tailpipe as either sulfuric acid, a sulfate which is a component of primary particulate matter, or as sulfur dioxide (SO₂). Sulfur dioxide is formed in the engine, and its conversion into sulfuric acid is a function of the type of aftertreatment and temperature in the tailpipe. If there is no aftertreatment (as is expected to be the case for engines meeting the 2004 standards), only about 2 percent of sulfur ends up being converted into sulfuric acid, with the remaining 98 percent being retained as SO₂. A large percentage of the SO₂ exiting the tailpipe is converted to sulfate (primarily ammonium sulfate) in the atmosphere. For engines meeting our 2007 standards, however, we expect the conversion rate of SO₂ to sulfuric acid to be much higher, closer to 30 percent, due to the use of particulate traps. Thus the calculation of tons of SO₂ reduced due to our program compares a baseline of 340 ppm and 98 percent SO₂ retention to a control of 7 ppm and 70 percent SO₂ retention.

Discounted lifetime tons of SO₂ reduced is calculated as the difference between tons of SO₂ for the baseline minus tons of SO₂ for our program, where tons are calculated according to the following equation:

$$LE = \sum [\{ (AVMT)_i \cdot (SURVIVE)_i \div (FE) \cdot (D) \cdot (SUL) \cdot (F) \cdot (MC) \cdot (CF) \cdot (K) \} / (1.07)^{i-1}]$$

Where:

LE	= Discounted lifetime emissions of SO ₂ in tons/engine for either the baseline or our control program
(AVMT) _i	= Annual engine miles traveled in year i of a engine's operational life
(SURVIVE) _i	= Fraction of engines still operating after i years of service
FE	= Fuel economy by engine class (see Appendix VI-A)
D	= Density of diesel, 7.1 lb/gal
SUL	= Diesel sulfur concentration, 3.4 x 10 ⁻⁴ lb sulfur/lb fuel (340 ppm) for the baseline and 0.07 x 10 ⁻⁴ lb sulfur/lb fuel (7 ppm) for our program
F	= Fraction of total sulfur which exits the tailpipe as SO ₂ (0.98 for baseline case and 0.70 for control case)
MC	= Molar conversion factor, 2 lb SO ₂ per lb sulfur
CF	= Heavy-duty engine conversion factor, bhp-hr/mile
K	= Mass conversion factor, 5.0 x 10 ⁻⁴ tons/lb
i	= Engine years of operation, counting from 1 to 30

After applying the above equation separately for each engine class and weighting the resulting tonnage values according to the factors presented in Table VI.C-2, we determined that the fleet-average, per-engine discounted lifetime tons of SO₂ reduced is 0.0929. This is the value that was used to determine the SO₂-based credit that was applied to the total costs as described in Section VI.B.4 and summarized in Table VI.B-2.

D. Costs and Emission Reductions for Heavy-duty Gasoline Vehicles

Since we are also proposing new standards for heavy-duty gasoline vehicles (HDGV), we have calculated the costs and tons reduced for these standards as well. We did this on a per-vehicle basis, consistent with our approach for diesel engines described above. However, unlike for our diesel engine standards, our HDGV standards are not associated with new gasoline specifications, since a standard of 30 ppm sulfur has already been set in the preceding Tier 2/gasoline sulfur rulemaking.

1. Gasoline Vehicle Costs

The impact of our standards for HDGV was discussed in Section III.B and the associated compliance costs were discussed in Section V.B.5. We have made use of the per-vehicle costs shown in Table V.B-5 in our cost-effectiveness analysis, assuming that near-term costs are represented by the 2008-2009 values, and long-term costs are represented by the 2013+ values. We weighted the costs for the incompletes, Class 2b completes, and Class 3 completes by their

respective contributions to the 2020 fleet (see Table VI.D-3). The fleet-average costs are repeated in Table VI.D-1 below.

Table VI.D-1. Fleet-average, Per-vehicle Costs for HDGV Used in Cost-effectiveness

	<i>Total costs (\$)</i>
Near-term	198
Long-term	167

2. Emission Reductions from Gasoline Vehicles

The discounted lifetime tonnage numbers for NOx and NMHC for our HDGV standards were based on the difference between emissions produced by vehicles meeting our 2005 and 2007 standards. Section II.B describes the base emission factors, conversions, and adjustments used to calculate the in-use emissions in grams/mile produced by HDGVs for each year of a vehicle's life. From this basis, lifetime tonnage estimates were developed using the following procedure:

- 1) Annual mileage accumulation levels for MOBILE6 were applied to the in-use emission rates for each year in a vehicle's life to generate total mass emissions produced in each year by that vehicle
- 2) The resultant mass emissions were multiplied by the probability of survival in the appropriate year, known as the "survival" rate.
- 3) A seven percent annual discount factor, compounded from the first year of the engine's life, was then applied for each year to allow calculation of net present value lifetime emissions.

Converting to tons and summing across all years results in the total discounted lifetime per-vehicle tons. This calculation can be described mathematically as follows:

$$LE = \sum [\{ (AVMT)_i \cdot (SURVIVE)_i \cdot (ER)_i \cdot (K) \} / (1.07)^{i-1}]$$

Where:

- LE = Discounted lifetime emissions in tons/vehicle
- (AVMT)_i = Annual miles traveled in year i of a HDGV's operational life
- (SURVIVE)_i = Probability of survival after i years of service
- (ER)_i = Emission rate, g/mi in year i of a vehicle's operational life
- K = Mass conversion factor, 1.102 x 10⁻⁶ tons/gram
- i = Vehicle years of operation, counting from 1 to 24

For NOx and NMHC, we generated discounted lifetime tonnage values for each vehicle class (incompletes, Class 2B completes, and Class 3 completes) using the above equation. This was done separately for the baseline and control cases. The baseline case included the 2005 model year vehicle standards, while the control case entailed our 2007 model year vehicle standards. The tonnage values that we calculated according to this procedure are shown in Table VI.D-2.

Table VI.D-2. Per-vehicle Discounted Lifetime Tons for HDGV

	<i>NOx + NMHC</i>
<u>Baseline</u>	
Incompletes	0.261
Class 2B completes	0.271
Class 3 completes	0.269
<u>Control</u>	
Incompletes	0.170
Class 2B completes	0.166
Class 3 completes	0.192

The final step before calculating the cost-effectiveness of our program was to weight the discounted lifetime tonnage values for each vehicle class by their respective fraction of the HDGV fleet. These fractions were based on vehicle count projections for 2020 for gasoline-powered heavy-duty vehicles, which in turn were based on current sales of new vehicles. Table VI.D-3 presents the final weighting factors we used to develop fleet-average tonnage values.

Table VI.D-3. Vehicle Class Sales Weighting Factors for HDGV

Incompletes	0.288
Class 2B completes	0.692
Class 3 completes	0.020

The final discounted lifetime tonnage values for an average fleet engine meeting either the 2005 or 2007 standards are shown in Table VI.D-4. It is these values that were used directly in calculating the cost-effectiveness of our program.

Table VI.D-4. Fleet average, Per-vehicle Discounted Lifetime Tons for HDGV

	<i>NO_x + NMHC</i>
Baseline: 2004 standards	0.268
Control: 2007 standards	0.167
Baseline - control	0.100

Note that although we are proposing new PM standards for HDGV in order to establish consistency with the HDDE PM standards, current HDGV are believed to already meet this PM standard. Therefore, there are no PM emission reductions associated with HDGV.

Since we are calculating a single set of cost-effectiveness values for both diesel engines and gasoline vehicles, it was necessary for us to weight the costs and emission reductions for HDDE and HDGV by the fraction of new diesel-powered and gasoline-powered heavy-duty vehicles in the fleet. These fractions are based on current sales of new vehicles, or the corresponding estimates of in-use vehicle counts far into the future. We have chosen 2020 to represent the far future for the purposes of this analysis. According to projections for MOBILE6, in year 2020 the in-use heavy-duty fleet will be composed of approximately 50 percent diesel-powered and 50 percent gasoline-powered vehicles. We applied this weighting to the NO_x+NMHC costs from Tables VI.B-2 and VI.D-1 to obtain per-vehicle costs representing all heavy-duty vehicles (PM reductions are only produced by our HDDE standards, so the PM cost-effectiveness values represent only HDDE). We likewise applied the 50:50 weighting to the NO_x+NMHC tons reduced from Tables VI.C-3 and VI.D-4. Final costs and tons reduced for the entire heavy-duty fleet on a per-vehicle basis are given in Table VI.F-1 below.

E. 30-year Net Present Value Cost-Effectiveness

The per-vehicle approach described in the preceding sections is designed to show the cost-effectiveness of our program for 2007 and later model year engines complying with our new standards. It presumes that all delays and the Temporary Compliance Option have been completed and the fleet has fully turned over to engines meeting our standards. However, the per-vehicle approach does not account for costs and emission reductions associated with the existing (pre-2007 model year) fleet due to operation on diesel fuel meeting our 15 ppm cap, nor does it take into account phased-in engine or temporary fuel provisions at the start of the program.

We have also calculated the cost effectiveness of our program using a “30-year net present value” approach that includes all nationwide emission reductions and costs for a 30 year period. This timeframe captures both the early period of the program when very few vehicles/engines meeting our standards will be in the fleet, and the later period when essentially all vehicles/engines in the fleet will meet our standards. The 30-year net present value approach also accounts for cost and emission impacts of our 15 ppm sulfur cap on engines manufactured before model year 2007. The 30-year net present value approach does have one important drawback in that it includes the engine costs for engines sold 30 years after the program goes into effect, but includes almost none of the emission benefits from those engines. Thus the 30-year net present value approach does not necessarily match all costs with all the emission reductions that those costs are intended to produce. It is presented here, nevertheless, as a reasonable measure of the cost effectiveness of this combined vehicle-fuel program.

We have calculated this “30-year net present value” cost-effectiveness using the net present value of the annual emission reductions and costs described in Sections II and V, respectively. The calculation of 30-year net present value cost-effectiveness follows the pattern described above for the per-engine analysis:

$$DNAE = \sum (NE)_i / (1.07)^{i-2006}$$

Where:

DNAE = Reduction in nationwide 30-year net present value emissions in tons
 (NE)_i = Reduction in nationwide emissions in tons for year i of the program
 i = Year of the program, counting from 2006 to 2035

and

$$DNAC = \sum (NC)_i / (1.07)^{i-2006}$$

Where:

- DNAC = Nationwide 30-year net present value costs in dollars
- (NC)_i = Nationwide costs in dollars for year i of the program
- i = Year of the program, counting from 2006 to 2035

The 30-year net present value cost-effectiveness is produced by dividing DNAC by DNAE. The nationwide reductions in emissions for each year are given in Section II. The nationwide costs are given in Table V.D-1. The results are given in Table VI.F-2 below.

F. Results

We calculated the cost-effectiveness of our standards using two different approaches. The first divides the total per-vehicle, discounted lifetime costs by the total per-vehicle, discounted lifetime tons reduced for our HDDE standards, diesel sulfur standard, and HDGV standards. The results are given in Table VI.F-1.

Table VI.F-1. Per-vehicle Cost-effectiveness of the Standards

<i>Pollutants</i>	<i>Discounted lifetime vehicle & fuel costs</i>	<i>Discounted lifetime emission reductions (tons)</i>	<i>Discounted lifetime cost effectiveness per ton</i>	<i>Discounted lifetime cost effectiveness per ton with SO₂ credit*</i>
<u>Near-term costs</u>				
NO _x + NMHC	1789	0.8421	2,125	2,125
PM	956	0.0672	14,237	7,599
<u>Long-term costs</u>				
NO _x + NMHC	1365	0.8421	1,621	1,621
PM	762	0.0672	11,340	4,701

* \$446 credited to SO₂ (at \$4800/ton) for PM cost effectiveness

We also calculated the cost-effectiveness of our program on a 30-year net present value basis for our diesel engine, diesel fuel sulfur, and gasoline vehicle standards. To do this, we summed net present value of total costs from Section V.D, and divided by the sum of the net present value of tons reduced from Sections II.B.2 and II.C. These costs and emission reductions are repeated in Appendices VI-B and VI-C. The results are given in Table VI.F-2.

Table VI.F-2. 30-year Net Present Value Cost-effectiveness of the Standards

	<i>30-year n.p.v. engine, vehicle, & fuel costs</i>	<i>30-year n.p.v. reduction (tons)</i>	<i>30-year n.p.v. cost effectiveness per ton</i>	<i>30-year n.p.v. cost effectiveness per ton with SO₂ credit*</i>
NO _x + NMHC	\$34.9 billion	16.2 million	\$2,149	\$2,149
PM	\$10.3 billion	0.8 million	\$13,607	\$4,195

* \$7.1 billion credited to SO₂ (at \$4800/ton)

The values in Tables VI.F-1 and VI.F-2 differ from those in the NPRM for several reasons. First, our estimate of costs increased for HDDE, HDGV, and diesel fuel sulfur as described in Section V. Second, the NMHC benefits associated with HDDE were reduced due to our re-evaluation of the means through which manufacturers would meet our new standards, as described in Section II.B. Third, our final program includes a phase-in for the engine standards and a Temporary Compliance Option for the fuel sulfur standards, which reduced both the costs and emission reductions in the first few years of the program.

Since many of the benefits and costs are manifest in future years, we apply discounting methods to adjust the dollar values of these effects to reflect the finding that society as a whole typically values the realization (or avoidance) of a given effect differently depending on when the effect occurs. In the discounting calculations used to produce the net present values that were used in our cost-effectiveness calculations, we used a discount rate of 7 percent, consistent with the 7 percent rate reflected in the cost-effectiveness analyses for other recent mobile source programs. OMB Circular A-94 requires us to generate benefit and cost estimates reflecting a 7 percent rate.

However, we anticipate that the primary cost and cost-effectiveness estimates for future proposed mobile source programs will reflect a 3 percent rate. The 3 percent rate is in the 2 to 3 percent range recommended by the Science Advisory Board's Environmental Economics Advisory Committee for use in EPA social benefit-cost analyses, a recommendation incorporated in EPA's new *Guidelines for Preparing Economic Analyses (November 2000)*. This recommendation was published after the current program was proposed. Therefore, we have also calculated the overall cost-effectiveness of today's rule based on a 3 percent rate to facilitate comparison of the cost-effectiveness of this rule with future proposed rules which use the 3 percent rate. The results are shown in Tables VI.F-3 and VI.F-4.

Table VI.F-3. Per-vehicle Cost-effectiveness of the Standards Using 3 Percent ROI and Discount Rate

<i>Pollutants</i>	<i>Discounted lifetime vehicle & fuel costs</i>	<i>Discounted lifetime emission reductions (tons)</i>	<i>Discounted lifetime cost effectiveness per ton</i>	<i>Discounted lifetime cost effectiveness per ton with SO₂ credit*</i>
<u>Near-term costs</u>				
NOx + NMHC	1860	0.9961	1,867	1,867
PM	1008	0.0786	12,817	6,168
<u>Long-term costs</u>				
NOx + NMHC	1452	0.9961	1,458	1,458
PM	821	0.0786	10,439	3,790

* \$523 credited to SO₂ (at \$4800/ton) for PM cost effectiveness.

Table VI.F-4. 30-year Net Present Value Cost-effectiveness of the Standards Using 3 Percent ROI and Discount Rate

	<i>30-year n.p.v. engine, vehicle, & fuel costs</i>	<i>30-year n.p.v. reduction (tons)</i>	<i>30-year n.p.v. cost effectiveness per ton</i>	<i>30-year n.p.v. cost effectiveness per ton with SO₂ credit*</i>
NOx + NMHC	\$54.6 billion	30.6 million	\$1,784	\$1,784
PM	\$16.0 billion	1.4 million	\$11,791	\$3,384

* \$11.4 billion credited to SO₂ (at \$4800/ton)

Because the primary purpose of cost-effectiveness is to compare our program to alternative programs, we made a comparison between the values in Tables VI.F-1 and VI.F-2 and the cost-effectiveness of other programs. Table VI.F-5 summarizes the cost effectiveness of several recent EPA actions for controlled emissions from mobile sources for NOx and NMHC, while Table VI.F-6 does the same for PM. The programs shown in these tables are those for which cost-effectiveness was calculated in a similar manner allowing for an apples-to-apples comparison.

Table VI.F-5. Cost-effectiveness of Previous Mobile Source Programs for NO_x + NMHC

<i>Program</i>	<i>\$/ton</i>
Tier 2 vehicle/gasoline sulfur	1,340 - 2,260
2004 Highway HD diesel	212 - 414
Off-highway diesel engine	425 - 675
Tier 1 vehicle	2,054 - 2,792
NLEV	1,930
Marine SI engines	1,171 - 1,846
On-board diagnostics	2,313
Marine CI engines	24 - 176

Note: costs adjusted to 1999 dollars.

Table VI.F-6. Cost-effectiveness of Previous Mobile Source Programs for PM

<i>Program</i>	<i>\$/ton</i>
Marine CI engines	5222 -3881
1996 urban bus	12,264 - 19,622
Urban bus retrofit/rebuild	30,251
1994 highway HD diesel	20,900 - 24,467

Note: costs adjusted to 1999 dollars.

By comparing values from Tables VI.F-1 and VI.F-2 for NO_x+NMHC to those in Table VI.F-5 we can see that the cost-effectiveness of our engine/diesel sulfur standards falls within the range of these other programs. Our program overlaps the range of the recently promulgated standards for Tier 2 light-duty vehicles and gasoline sulfur shown in Table VI.F-5. Our program also overlaps the cost-effectiveness of past programs for PM. It is true that some previous programs have been more cost efficient than the program we are proposing today. However, it should be expected that the next generation of standards will be more expensive than the last, since the least costly means for reducing emissions is generally pursued first.

The primary advantage of making comparisons to previously implemented programs is that their cost-effectiveness values were based on a rigorous analysis and are generally accepted as representative of the efficiency with which those programs reduce emissions. Unfortunately, previously implemented programs can be poor comparisons because they may not be representative of the cost-effectiveness of potential future programs. Therefore, in evaluating the cost-effectiveness of our engine/diesel sulfur program, we also considered whether our proposal

is cost-effective in comparison with potential future means of controlling emissions. In the context of the Agency's rulemaking which would have revised the ozone and PM NAAQS², the Agency compiled a list of additional known technologies that could be considered in devising new emission reductions strategies.⁵ Through this broad review, over 50 technologies were identified that could reduce NO_x, VOC, or PM. The cost-effectiveness of these technologies averaged approximately \$5,000/ton for VOC, \$13,000/ton for NO_x, and \$40,000/ton for PM. Although a \$10,000/ton limit was actually used in the air quality analysis presented in the NAAQS revisions rule, these values clearly indicate that, not only are future emission control strategies likely to be more expensive (less cost-effective) than past strategies, but the cost-effectiveness of our engine/diesel sulfur program falls within the range of potential future strategies.

In summary, given the array of controls that will have to be implemented to make progress toward attaining and maintaining the NAAQS, we believe that the weight of the evidence from alternative means of providing substantial NO_x + NMHC and PM emission reductions indicates that our engine/diesel sulfur program is cost-effective. This is true from the perspective of other mobile source control programs or from the perspective of other stationary source technologies that might be considered.

^b This rulemaking was remanded by the D.C. Circuit Court on May 14, 1999. However, the analyses completed in support of that rulemaking are still relevant, since they were designed to investigate the cost-effectiveness of a wide variety of potential future emission control strategies.

APPENDIX VI - A: Factors Used in Diesel Engine Calculations for Cost-effectiveness

<i>MOBILE6 engine class</i>	<i>Weight category^A</i>	<i>Sales weighting^B</i>	<i>Conversion factors, bhp-hr/mi^B</i>	<i>Fuel economy, miles/gal^D</i>
Class 2B	LH	0.199	1.09	12.96
Class 3	LH	0.060	1.25	11.66
Class 4	LH	0.056	1.458	10.2
Class 5	LH	0.027	1.573	9.88
Class 6	MH	0.115	1.942	8.71
Class 7	MH	0.164	2.409	7.53
Class 8A	HH	0.098	2.763	6.59
Class 8B	HH	0.227	3.031	6.3
School buses	MH	0.044	2.989	6.18
Urban transit buses	HH	0.009	4.679	3.79

^A LH = Light heavy duty, MH = Medium heavy duty, HH = Heavy heavy duty.

^B Based on 2020 heavy-duty diesel engine count, Tables 17 & 18 from EPA Report Number EPA420-P-99-011, April 1999, "Fleet characterization data for MOBILE6: development and use of age distributions, average annual mileage accumulation rates and projected vehicle counts for use in MOBILE6."

^C Tables 28 and 30 from EPA Report Number EPA420-P-98-015, May 1998, "Update heavy-duty engine emission conversion factors for MOBILE6: Analysis of BSFCs and calculation of heavy-duty engine emission conversion factors."

^D Tables 14 and 15 from EPA Report Number EPA420-P-98-014, May 1998, "Update heavy-duty engine emission conversion factors for MOBILE6: Analysis of fuel economy, non-engine fuel economy improvements, and fuel densities."

APPENDIX VI - B: Costs used in 30-year Net Present Value Cost Effectiveness Analysis (\$millions)

	<i>Diesel NOx adsorber + oxy catalyst</i>	<i>Diesel PM trap</i>	<i>Gasoline vehicle</i>	<i>Diesel sulfur</i>
2006	(49)	(32)	0	880
2007	765	501	0	1,786
2008	798	523	46	1,809
2009	648	425	80	1,904
2010	918	602	81	2,014
2011	740	485	82	2,128
2012	684	449	83	2,160
2013	699	458	78	2,192
2014	713	467	79	2,225
2015	689	452	80	2,258
2016	698	458	82	2,292
2017	700	459	83	2,327
2018	714	468	84	2,362
2019	728	477	85	2,397
2020	741	486	86	2,433
2021	753	494	87	2,469
2022	766	502	89	2,506
2023	778	510	90	2,544
2024	789	518	91	2,582
2025	801	525	92	2,621
2026	812	532	93	2,660
2027	823	540	94	2,700
2028	834	547	95	2,741
2029	844	554	97	2,782
2030	855	561	98	2,824
2031	865	567	99	2,866
2032	876	574	100	2,909
2033	886	581	101	2,953
2034	896	588	102	2,997
2035	906	594	104	3,042

APPENDIX VI - C: Emission Reductions Used in 30-year Net Present Value Cost Effectiveness Analysis (thousand tons)

	<i>Diesel NOx</i>	<i>Diesel VOC</i>	<i>Diesel PM</i>	<i>Diesel SOx</i>	<i>Gasoline NOx</i>	<i>Gasoline VOC</i>
2006	0	0	5	78	0	0
2007	58	2	11	79	0	0
2008	160	7	19	80	2	1
2009	255	12	27	82	7	2
2010	406	17	35	107	13	5
2011	599	22	41	109	19	7
2012	776	27	46	111	24	9
2013	939	32	51	113	29	10
2014	1,090	37	56	115	34	12
2015	1,228	43	61	117	38	13
2016	1,356	47	65	119	43	15
2017	1,473	52	69	121	48	16
2018	1,581	56	73	122	51	18
2019	1,680	60	77	124	55	20
2020	1,772	64	82	126	58	21
2021	1,857	66	85	128	63	23
2022	1,939	69	88	129	67	24
2023	2,017	71	91	131	70	25
2024	2,091	74	93	133	72	26
2025	2,163	76	96	134	75	27
2026	2,232	78	99	136	78	28
2027	2,299	80	101	137	80	29
2028	2,364	83	104	139	83	30
2029	2,428	85	106	140	86	31
2030	2,490	87	109	142	88	32
2031	2,552	89	111	143	91	33
2032	2,615	91	113	144	94	34
2033	2,677	93	116	146	96	35
2034	2,739	94	118	147	99	36
2035	2,801	96	120	149	102	37

Chapter VI. References

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5. "Regulatory Impact Analyses for the Particulate Matter and Ozone National Ambient Air Quality Standards and Regional Haze Rule," Appendix B, "Summary of control measures in the PM, regional haze, and ozone partial attainment analyses," Innovative Strategies and Economics Group, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, July 17, 1997.

Chapter VII: Benefit-Cost Analysis

This chapter reports EPA's analysis of the economic benefits of the final HD Engine/Diesel Fuel rule. EPA is required by Executive Order 12866 to estimate the benefits of major new pollution control regulations. Accordingly, the analysis presented here attempts to answer three questions: 1) what are the physical health and welfare effects of changes in ambient air quality resulting from reductions in nitrogen oxides (NO_x), sulfur dioxide (SO₂), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and direct diesel particulate matter (PM) emissions?; 2) how much are the changes in air quality worth to U.S. citizens as a whole in monetary terms?; and 3) how do the benefits compare to the costs? It constitutes one part of EPA's thorough examination of the relative merits of this regulation.

The benefit-cost analysis that we performed for our final rule can be thought of as having four parts, each of which will be discussed separately in the Sections that follow. These four steps are:

1. Calculation of the impact that our standards will have on the nationwide inventories for NO_x, non-methane hydrocarbons (NMHC), SO₂, and PM emissions;
2. Air quality modeling to determine the changes in ambient concentrations of ozone and PM that will result from the changes in nationwide inventories of precursor pollutants;
3. A benefits analysis to determine the changes in human health and welfare, both in terms of physical effects and monetary value, that result from the changes in ambient concentrations of various pollutants; and
4. Comparison of the costs of the standards to the monetized benefits.

It is important to note that there are significant categories of benefits which can not be monetized (or in many cases even quantified), resulting in a significant limitation to this analysis. Also, EPA currently does not have appropriate tools for modeling changes in ambient concentrations of CO or air toxics for input into a national benefits analysis. They have been linked to numerous health effects; however, we are unable to quantify the CO- or air toxics-related health or welfare benefits of the HD Engine/Diesel Fuel rule at this time.

EPA has used the best available information and tools of analysis to quantify the expected changes in public health, environmental and economic benefits of the final HD Engine/Diesel Fuel rule, given the constraints on time and resources available for the analysis. In general, we

follow the same general methodology used in the benefits analysis of the Tier 2/Gasoline Sulfur rulemaking. However, we have updated some aspects of the analysis in response to public comment and to reflect advances in modeling and the literature for economics and health effects. EPA also relies heavily on the advice of its independent Science Advisory Board (SAB) in determining the health and welfare effects considered in the benefits analysis and in establishing the most scientifically valid measurement and valuation techniques. Since the publication of the final Tier 2/Gasoline Sulfur RIA, we have updated some of the assumptions and methods used in our analysis to reflect SAB recommendations. Changes to the methodology include the following:

- Using Regulatory Model System for Aerosols and Deposition (REMSAD) to model baseline and post-control ambient particulate matter;
- Updating concentration-response (C-R) functions for PM-related premature mortality;
- Updating C-R functions for PM-related hospital admissions;
- Presenting chronic asthma as an alternative calculation;
- Reporting asthma attacks as a separate endpoint and adjusting minor restricted activity days to remove the possibility of double-counting of asthma attacks;
- Relying only on the value of statistical life method to value reductions in the risk of premature mortality in the primary estimate; and
- Adjusting benefits to reflect the expected growth in willingness-to-pay (WTP) for health and environmental benefits as real income grows over time.

All of these changes are expected to improve the quality of the benefits estimation. These changes reflect the latest peer-reviewed scientific literature and most of the improvements have been approved by the SAB in its review of EPA methods in other analyses. A detailed discussion of each change is included in the body of this chapter.

We have attempted to be as clear as possible in presenting our assumptions, sources of data, and sources of potential uncertainty in the analysis. We urge the reader to pay particular attention to the fact that not all the benefits of the rule can be estimated with sufficient reliability to be quantified and included in monetary terms. Some welfare endpoints, for instance, are quantified to some extent but no dollar value can be reliably assigned. The omission of these items from the total of monetary benefits reflects our inability to measure them. It does not

indicate their lack of importance in the consideration of the benefits of this rulemaking. When it is possible to qualitatively characterize a benefits category, we provide a discussion, although the benefit is not included in the estimate of total benefits.

We use the term *benefits* to refer to any and all positive effects of emissions changes on social welfare that we expect to result from the final rule. We use the term environmental costs (also commonly referred to as “disbenefits”) to refer to any and all negative effects of emissions changes on social welfare that result from the final rule. We include both benefits and environmental costs in this analysis. Where it is possible to quantify benefits and environmental costs, our measures are those associated with economic surplus in accepted applications of welfare economics. They measure the value of changes in air quality by estimating (primarily through benefits transfer) the willingness of the affected population to pay for changes in environmental quality and associated health and welfare effects.

This analysis presents estimates of the potential benefits from the HD Engine/Diesel Fuel rule occurring in 2030. The predicted emissions reductions that will result from the rule have yet to occur, and therefore the actual changes in human health and welfare outcomes to which economic values are ascribed are predictions. These predictions are based on the best available scientific evidence and judgment, but there is unavoidable uncertainty associated with each step in the complex process between regulation and specific health and welfare outcomes. The ways in which we deal with these uncertainties are discussed in Section C.

Figure VII-1 illustrates the steps necessary to link the HD Engine/Diesel Fuel rule with economic measures of benefits. The first two steps involve the specification and implementation of the regulation. First, the specific standards for reducing air pollution from heavy duty vehicles and fuels are established. Next, the necessary changes in vehicle technology and fuels are determined (see Chapters IV and V). The changes in pollutant emissions resulting from the required vehicle and fuel changes are then calculated, along with predictions of emissions for other industrial sectors in the baseline. The predicted emissions described in Chapter III are then used as inputs to air quality models that predict ambient concentrations of pollutants over time and space. These concentrations depend on climatic conditions and complex chemical interactions. We have used the best available air quality models to estimate the changes in ambient concentrations (from baseline levels) used as the basis for this benefits analysis.

Changes in ambient concentrations will lead to new levels of environmental quality in the U.S., reflected both in human health and in non-health welfare effects. Thus, the predicted changes in ambient air quality serve as inputs into functions that predict changes in health and welfare outcomes. We use the term “endpoints” to refer to specific effects that can be associated with changes in air quality. Table VII-1 lists the human health and welfare effects identified for

changes in air quality as they related to ozone, PM, CO, and NMHC.^a This list includes both those effects quantified (and/or monetized) in this analysis and those for which we are unable to provide quantified estimates. All of the effects related to changes in CO and NMHC are not directly quantified for this analysis due to a lack of appropriate air quality models for these pollutants. For changes in risks to human health from changes in ozone and PM, quantified endpoints include changes in mortality and in a number of pollution-related non-fatal health effects. To estimate these endpoints, EPA combines changes in ambient air quality levels with epidemiological evidence about population health response to pollution exposure. For welfare effects, the endpoints are defined in terms of levels of physical damage (for materials damage), economic output for (agriculture and forestry), light transmission (for visibility), and increases in terrestrial and estuarine nutrient loading (for ecological effects).

As with emissions and air quality estimates, EPA's estimates of the effect of ambient pollution levels on all of these endpoints represent the best science available. The majority of the analytical assumptions used to develop our estimates have been reviewed and approved by the SAB. However, like all estimates, they also contain unavoidable uncertainty, as does any prediction of the future. In Section C and its subsections on health and welfare endpoints, this uncertainty is discussed and characterized.

This chapter proceeds as follows: in Sections A and B, we summarize emissions and air quality results and discuss the way emissions and air quality changes are used as inputs to the benefits analysis. In Section C, we introduce the categories of benefits that are estimated, present the techniques that are used, and provide a discussion of how we incorporate uncertainty into our analysis. In Section D, we describe individual health effects and report the results of the analysis for human health effects. In Section E, we describe welfare effects and report the results of the analysis for welfare effects. In Section F, we report our estimates of total monetized benefits and alternative calculations of benefits. Finally, in Section G, we summarize annual cost results and in Section H, we present a comparison of monetized benefits and costs.

^a The NMHC listed in Table VII-1 are also listed as hazardous air pollutants in the Clean Air Act. We are not able to quantify their direct effects. To the extent that they are precursors to ozone or PM, they are included in our quantitative results.

Figure VII-1. Steps in the Heavy Duty Engine/Diesel Fuel Benefits Analysis

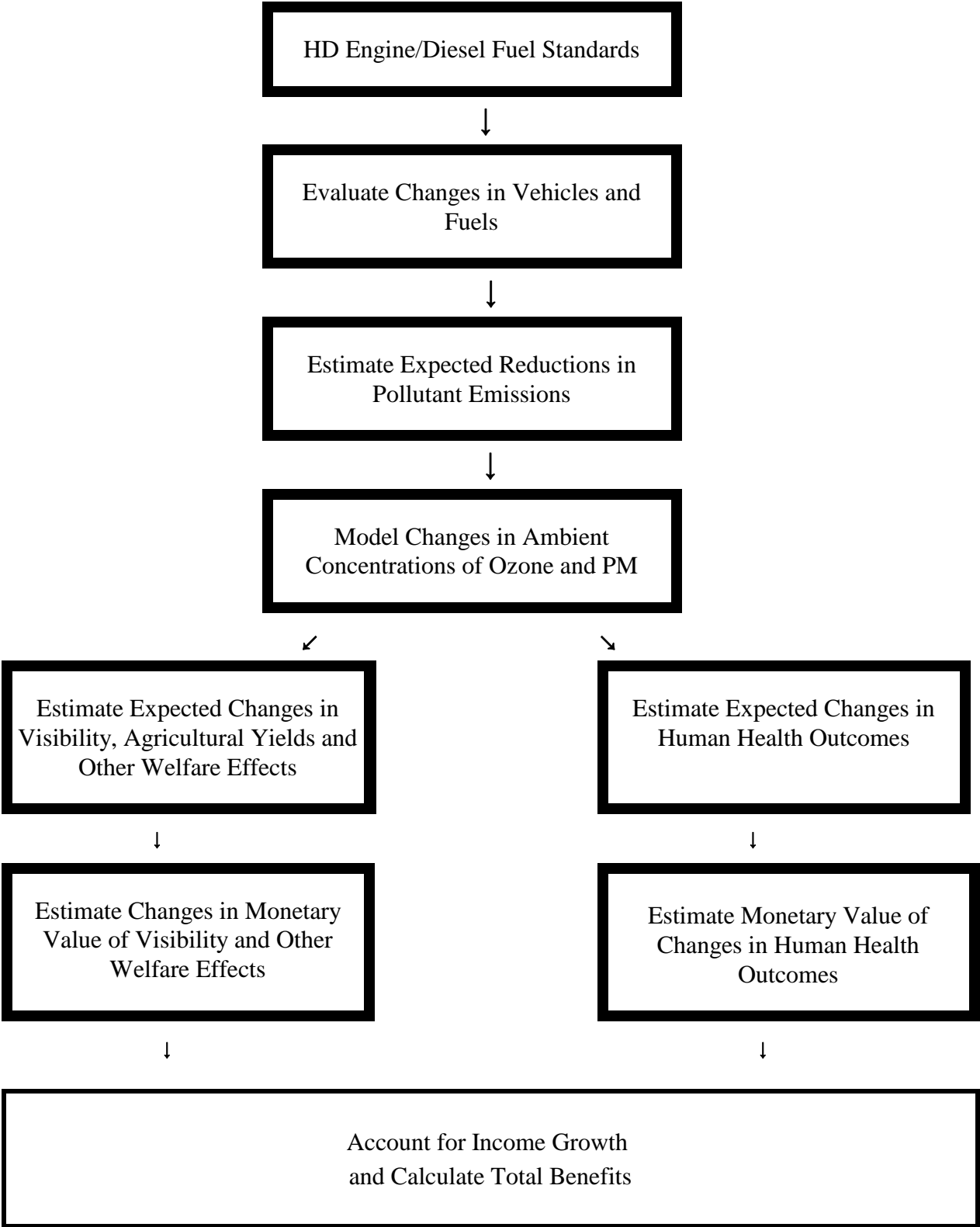


Table VII-1. Human Health and Welfare Effects of Pollutants Affected by the HD Engine/Diesel Fuel Rule

Pollutant/Effect	Primary Quantified and Monetized Effects^A	Alternative Quantified and/or Monetized Effects^B	Unquantified Effects
Ozone/Health	Minor restricted activity days Hospital admissions - respiratory and cardiovascular Emergency room visits for asthma Asthma attacks	Chronic Asthma ^C	Premature mortality ^D Increased airway responsiveness to stimuli Inflammation in the lung Chronic respiratory damage Premature aging of the lungs Acute inflammation and respiratory cell damage Increased susceptibility to respiratory infection Non-asthma respiratory emergency room visits
Ozone/Welfare	Decreased worker productivity Decreased yields for commercial crops (selected species) Decreased Eastern commercial forest productivity (selected species)		Decreased Western commercial forest productivity Decreased Eastern commercial forest productivity (other species) Decreased yields for fruits and vegetables Decreased yields for other commercial and non-commercial crops Damage to urban ornamental plants Impacts on recreational demand from damaged forest aesthetics Damage to ecosystem functions
PM/Health	Premature mortality Bronchitis - chronic and acute Hospital admissions - respiratory and cardiovascular Emergency room visits for asthma Asthma attacks Lower and upper respiratory illness Minor restricted activity days Work loss days		Infant mortality Low birth weight Changes in pulmonary function Chronic respiratory diseases other than chronic bronchitis Morphological changes Altered host defense mechanisms Cancer Non-asthma respiratory emergency room visits

Pollutant/Effect	Primary Quantified and Monetized Effects^A	Alternative Quantified and/or Monetized Effects^B	Unquantified Effects
PM/Welfare	Visibility in California, Southwestern, and Southeastern Class I areas	Visibility in Northeastern, Northwestern, and Midwestern Class I areas Visibility in residential and non-Class I areas Household soiling	
Nitrogen and Sulfate Deposition/Welfare		Costs of nitrogen controls to reduce eutrophication in selected eastern estuaries	Impacts of acidic sulfate and nitrate deposition on commercial forests Impacts of acidic deposition on commercial freshwater fishing Impacts of acidic deposition on recreation in terrestrial ecosystems Impacts of nitrogen deposition on commercial fishing, agriculture, and forests Impacts of nitrogen deposition on recreation in estuarine ecosystems Reduced existence values for currently healthy ecosystems
SO₂/Health			Hospital admissions for respiratory and cardiac diseases Respiratory symptoms in asthmatics
NO_x/Health			Lung irritation Lowered resistance to respiratory infection Hospital Admissions for respiratory and cardiac diseases

Pollutant/Effect	Primary Quantified and Monetized Effects ^A	Alternative Quantified and/or Monetized Effects ^B	Unquantified Effects
CO/Health			Premature mortality ^B Behavioral effects Hospital admissions - respiratory, cardiovascular, and other Other cardiovascular effects Developmental effects Decreased time to onset of angina Non-asthma respiratory ER visits
NMHCs ^E Health			Cancer (diesel PM, benzene, 1,3-butadiene, formaldehyde, acetaldehyde) Anemia (benzene) Disruption of production of blood components (benzene) Reduction in the number of blood platelets (benzene) Excessive bone marrow formation (benzene) Depression of lymphocyte counts (benzene) Reproductive and developmental effects (1,3-butadiene) Irritation of eyes and mucous membranes (formaldehyde) Respiratory and respiratory tract Asthma attacks in asthmatics (formaldehyde) Asthma-like symptoms in non-asthmatics (formaldehyde) Irritation of the eyes, skin, and respiratory tract (acetaldehyde) Upper respiratory tract irritation & congestion (acrolein)

Pollutant/Effect	Primary Quantified and Monetized Effects^A	Alternative Quantified and/or Monetized Effects^B	Unquantified Effects
NMHCs^E Welfare			Direct toxic effects to animals Bioaccumulation in the food chain

^A Primary quantified and monetized effects are those included when determining the primary estimate of total monetized benefits of the HD Engine/Diesel Fuel rule. See Section C-2 for a more complete discussion of presentation of benefits estimates.

^B Alternative quantified and/or monetized effects are those presented as alternatives to the primary estimates or in addition to the primary estimates, but not included in the primary estimate of total monetized benefits.

^C While no causal mechanism has been identified linking new incidences of chronic asthma to ozone exposure, an epidemiological study shows a statistical association between long-term exposure to ozone and incidences of chronic asthma in some non-smoking men (McDonnell, et al., 1999).

^D Premature mortality associated with ozone is not separately included in this analysis. It is assumed that the American Cancer Society (ACS)/ Krewski, et al., 2000 C-R function we use for premature mortality captures both PM mortality benefits and any mortality benefits associated with other air pollutants (ACS/ Krewski, et al., 2000).

^E All non-methane hydrocarbons (NMHCs) listed in the table are also hazardous air pollutants listed in the Clean Air Act.

A. Emissions Inventory Implications

This section explains why 2030 emission inventories were developed and what the possible implications are for this benefit-cost analysis of uncertainties associated with the inventories. The national inventories for NO_x, NMHC, SO₂, and PM have already been presented and discussed in Chapter III and in the supporting documents referenced in that chapter. Interested readers desiring more information about the inventory methodologies or results should consult that chapter for details.

The HD Engine/Diesel Fuel program has various cost and emission related components, as described earlier in this RIA. These components would begin at various times and in some cases would phase in over time. This means that during the early years of the program there would not be a consistent match between cost and benefits. This is especially true for the vehicle control portions and initial fuel changes required by the program, where the full vehicle cost would be incurred at the time of vehicle purchase, while the fuel cost along with the emission reductions and benefits resulting from all these costs would occur throughout the lifetime of the vehicle. Because of this inconsistency and our desire to more appropriately match the costs and emission reductions of our program, our analysis uses a future year when the fleet is nearly fully turned over (2030). Consequently, we developed emission inventories for 2030 baseline conditions and a 2030 HD Engine/Diesel Fuel control scenario.

In the years before 2030, the benefits from the HD Engine/Diesel Fuel program will be less than those estimated here, because the compliant heavy-duty fleet will not be fully phased in. Moreover, to the extent that a lower ratio of benefits to costs early in the program is the result of the mismatch of costs and benefits in time, a simple analysis of an individual year would be misleading. A more appropriate means of capturing the impacts of timing differences in benefits and costs would be to produce a net present value comparison of the costs and benefits over some period of years. Unfortunately, while this is relatively straight-forward for the costs, it is currently not feasible to do a multi-year analysis of the benefits as this would require a significant amount of air quality modeling to capture each year. We did not have the resources for such an extensive analysis. Instead, for the purpose of the benefit calculations, we assume that 2030 is a representative year for the fully implemented rule to consider in comparison with the costs. The resulting analysis represents a snapshot of benefits and costs in a future year in which the heavy duty fleet consists almost entirely of vehicles and fuels meeting the HD Engine/Diesel Fuel standards.

In addition, there is uncertainty in any prediction, and the emissions inventory growth factors can add uncertainty because they are applied for a 30-year period and propagate through the entire analysis. This uncertainty may be more important for welfare effects such as ozone-related crop damage where the predicted 2030 baseline may be an important factor. These

exposure metrics for crop damage and forestry impacts are a cumulative measure above a certain level (i.e., 0.06 ppm). Thus, the accuracy of the emissions inventory growth rates can affect the magnitude of the benefits (For discussion see Section E). This is less of an issue for exposure metrics that rely on changes in air quality (e.g., the health endpoints). Nevertheless, the inventory is a crucial building block on which the analysis rests.

B. Air Quality Impacts

This section summarizes the methods for and results of estimating air quality for the 2030 base case and HD Engine/Diesel Fuel control scenario for the purposes of benefit-cost analyses. EPA has focused on the health, welfare, and ecological effects that have been linked to air quality changes. These air quality changes include the following:

- Ambient ozone—as estimated using a regional-scale version of the Urban Airshed Model-Variable Grid (UAM-V);
- Ambient particulate matter (PM₁₀ and PM_{2.5})—as estimated using a national-scale version of the Regulatory Modeling System for Aerosols and Deposition (REMSAD);
- Visibility degradation (i.e., regional haze), as developed using empirical estimates of light extinction coefficients and efficiencies in combination with REMSAD modeled reductions in pollutant concentrations; and
- Airborne nitrogen deposition to estuaries—as predicted using local and regional coefficients of nitrogen deposition for selected estuaries from the Regional Acid Deposition Model (RADM) in combination with modeled reductions in NO_x emissions.

The air quality estimates in this section are based on the emission changes discussed in Chapter III. These air quality results are in turn associated with human populations and ecosystems to estimate changes in health and welfare effects.

In Section B-1, we describe the estimation of ozone air quality using UAM-V, and in Section B-2, we cover the estimation of PM air quality using REMSAD. In Section B-3, we discuss the estimation of visibility degradation. Lastly, in Section B-4 we describe the estimation of nitrogen deposition.

1. Ozone Air Quality Estimates

We use the emissions inputs described in Section A with a regional-scale version of UAM-V to estimate ozone air quality in the Eastern U.S. UAM-V is an Eulerian three-dimensional grid photochemical air quality model designed to calculate the concentrations of both inert and chemically reactive pollutants by simulating the physical and chemical processes in the atmosphere that affect ozone formation. Because it accounts for spatial and temporal variations as well as differences in the reactivity of emissions, the UAM-V is useful for evaluating the impacts of the HD Engine/Diesel Fuel rule on U.S. ozone concentrations. As described fully in the air quality technical support document, the model performance in the Western U.S. was not acceptable for including those results as inputs to the benefits analysis (US EPA, 2000). Comparisons of base year model output data against ambient observations in the Western U.S. indicated that the model was significantly underestimating (by 30-50 percent) the observed levels of ozone in most areas of the West. Given that model performance was degraded to the extent that the directional response of the model to controls may be questionable, it was determined that this application of the model should not be used in assessing the impacts of the emissions control strategy in the Western U.S.

Thus, our analysis applies the modeling system to the Eastern U.S. for a base-year of 1996 and for two future-year scenarios: a 2030 base case and a 2030 HD Engine/Diesel Fuel control scenario. As discussed in the technical support document, we use the two separate years because the relative model predictions are used with ambient air quality observations from 1996 to determine the expected change in 2030 ozone concentrations due to the rule (Abt Associates, 2000).

The UAM-V modeling system requires a variety of input files that contain information pertaining to the modeling domain and simulation period. These include gridded, day-specific emissions estimates and meteorological fields, initial and boundary conditions, and land-use information. As applied to the Eastern region of the continental U.S., the model segments the area within the region into square blocks called grids (roughly equal in size to counties), each of which has several layers of air conditions that are considered in the analysis. Using this data, the UAM-V model generates predictions of hourly ozone concentrations for every grid. We then calibrate the results of this process to develop 2030 ozone profiles at monitor sites by normalizing the observations to the actual 1996 ozone data at each monitor site. For areas (grids) without ozone monitoring data, we interpolated ozone values using data from monitors surrounding the area. After completing this process, we calculated daily and seasonal ozone metrics to be used as inputs to the health and welfare C-R functions of the benefits analysis. The following sections provide a more detailed discussion of each of the steps in this evaluation and a summary of the results.

a. Modeling Domain

The modeling domain representing the Eastern U.S. is the same as that used in EPA's "Regulatory Impact Analysis for the NO_x SIP Call, FIP, and Section 126 Petitions" (US EPA, 1998b). As shown in Figure VII-2, this domain encompasses most of the Eastern U.S. from the East coast to mid-Texas and consists of two grids with differing resolutions. The shaded area of Figure VII-2 uses a relatively fine grid of 12 km consisting of nine vertical layers. The unshaded area of Figure VII-2 has less horizontal resolution, as it uses a 36 km grid with the same nine vertical layers. The vertical height of the modeling domain is 4,000 meters above ground level, for both the shaded and unshaded regions. The split between Eastern and Western counties is made at the 100th degree longitude (which runs through North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas).

b. Simulation Periods

For use in this benefits analysis, the simulation periods modeled by UAM-V included several multi-day periods when ambient measurements recorded high ozone concentrations. A simulation period, or episode, consists of meteorological data characterized over a block of days

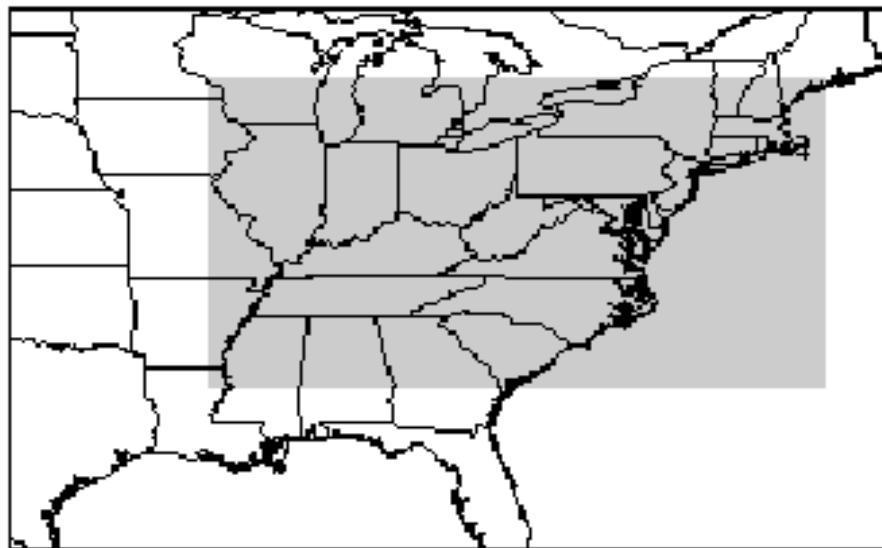


Figure VII-2. UAM-V Modeling Domain for Eastern U.S.

Note: The shaded section represents fine grid modeling (12 km) and the other portions represent coarse grid modeling (36 km).

that are used as inputs to the air quality model. A simulation period is selected to characterize a variety of ozone conditions including some days with high ozone concentrations in one or more portions of the U.S. and observed exceedances of the 1-hour NAAQS for ozone being recorded at monitors. We focused on the summer of 1995 for selecting the episodes to model in the East because 1995 is a recent time period for which we had model-ready meteorological inputs and this timeframe contained several periods of elevated ozone over the Eastern U.S. As detailed in the technical support document for this modeling, this analysis used three multi-day simulation periods to prepare the future-year ozone profiles for the Eastern U.S. ozone analysis: June 12-24, July 5-15, and August 7-21, 1995 (US EPA, 2000). These episodes include a three day “ramp-up” period to initialize the model, but the results for these days are not used in this analysis.

c. Converting UAM-V Outputs to Full-Season Profiles for Benefits Analysis

This study extracted hourly, surface-layer ozone concentrations for each grid-cell from the standard UAM-V output file containing hourly average ozone values. These model predictions are used in conjunction with the observed concentrations obtained from the Aerometric Information Retrieval System (AIRS) to generate ozone concentrations for the entire ozone season.^{b,c} The predicted changes in ozone concentrations from the 2030 base case to 2030 HD Engine/Diesel Fuel control scenario serve as inputs to the health and welfare C-R functions of the benefits analysis, i.e., the Criteria Air Pollutant Modeling System (CAPMS).

In order to estimate ozone-related health and welfare effects for the contiguous U.S., full-season ozone data are required for every CAPMS grid-cell. Given available ozone monitoring data, we generated full-season ozone profiles for each location in the contiguous 48 States in two steps: (1) we combine monitored observations and modeled ozone predictions to interpolate hourly ozone concentrations to a grid of 8 km by 8 km population grid-cells, and (2) we converted these full-season hourly ozone profiles to an ozone measure of interest, such as the daily average.^{d,e} For the analysis of ozone impacts on agriculture and commercial forestry, we use a similar approach except air quality is interpolated to county centroids as opposed to

^b The ozone season for this analysis is defined as the 5-month period from May to September; however, to estimate certain crop yield benefits, the modeling results were extended to include months outside the 5-month ozone season.

^c Based on AIRS, there were 949 ozone monitors with sufficient data, i.e., at least 9 hourly observations per day (8 am to 8 pm) in a given season.

^d The 8 km grid squares contain the population data used in the health benefits analysis model, CAPMS. See Section C of this chapter for a discussion of this model.

^e This approach is a generalization of planar interpolation that is technically referred to as enhanced Voronoi Neighbor Averaging (EVNA) spatial interpolation (See Abt Associates (2000) for a more detailed description).

population grid-cells. We report ozone concentrations as a cumulative index called the SUM06. The SUM06 is the sum of the ozone concentrations for every hour that exceeds 0.06 parts per million (ppm) within a 12-hour period from 8 am to 8 pm in the months of May to September. These methods are described in detail in the technical support document to the RIA (Abt Associates, 2000).

d. Ozone Air Quality Results

This section provides a summary the predicted ambient ozone concentrations from the UAM-V model for the 2030 base case and changes associated with the HD Engine control scenario. In Table VII-2, we provide those ozone metrics for grid-cells in the Eastern U.S. that enter the concentration response functions for health benefits endpoints. In addition to the standard frequency statistics (e.g., minimum, maximum, average, median), Table VII-2 provides the population-weighted average which better reflects the baseline levels and predicted changes for more populated areas of the nation. This measure, therefore, will better reflect the potential benefits of these predicted changes through exposure changes to these populations. As shown, the rule results in reductions between 3 and 5 percent, or between 0.8 to 1.7 ppb, in the daily and seasonal average ozone concentrations across Eastern U.S. population grid-cells. A similar relative decline is predicted for the population-weighted average, which indicates rather uniform reductions in these concentrations across urban and rural areas. Additionally, the daily maximum ozone concentrations are predicted to decline between 3.5 and 5 percent, or in the neighborhood of 1.5 ppb.

In Table VII-3, we provide the seasonal SUM06 ozone metric for counties in the Eastern U.S. that enters the concentration response function for agriculture benefit end-points. This metric is a cumulative threshold measure so that the increase in baseline NOx emissions from Tier 2 post-control to this rulemaking have resulted in a larger number of rural counties exceeding the hourly 0.06 ppm threshold. As a result, changes in ozone concentrations for these counties are contributing to greater impacts of the HD Engine/Diesel Fuel rule on the seasonal SUM06 ozone metric. Table VII-3 indicates that the average across all Eastern U.S. counties declined by 78 percent, or almost 17 ppb. Similarly high percentage reductions are observed across the other points on the distribution with the maximum declining by almost 30 ppb, or 55 percent, and the median declining by almost 20 ppb, or 83 percent.

An important factor to consider when interpreting the ozone air quality results presented here is the omission of changes in the Western U.S. Over 22 percent of national NOx emission reductions occur in the Western U.S., with over 10 percent of total NOx emissions occurring in California alone. This suggests that ozone changes in the West may be substantial, and that our estimate of Eastern ozone changes may underestimate populations across the nation that will experience ozone-related benefits of the HD Engine/Diesel Fuel NOx reductions.

Table VII-2. Summary of UAM-V Derived Ozone Air Quality Metrics Due to HD Engine/Diesel Fuel Standards for Health Benefits EndPoints: Eastern U.S.

<i>Statistic^A</i>	<i>2030 Base Case</i>	<i>Change^B</i>	<i>Percent Change^B</i>
<i>Seasonal Average 8-Hour Concentration (ppb)</i>			
Minimum ^C	17.60	-1.20	-6.82%
Maximum ^C	81.80	-3.20	-3.91%
Average	34.93	-1.64	-4.65%
Median	34.90	-1.67	-4.78%
Population-Weighted Average ^D	37.76	-1.43	-3.88%
<i>Daily 1-Hour Maximum Concentration (ppb)</i>			
Minimum ^C	22.11	-1.37	-6.20%
Maximum ^C	108.27	-3.66	-3.38%
Average	44.15	-1.68	-3.81%
Median	43.94	-1.57	-3.57%
Population-Weighted Average ^D	49.69	-1.71	-3.44%
<i>Daily 5-Hour Maximum Concentration (ppb)</i>			
Minimum ^C	18.21	-1.32	-7.25%
Maximum ^C	84.43	-3.27	-3.87%
Average	34.96	-1.64	-4.69%
Median	34.98	-2.13	-6.09%
Population-Weighted Average ^D	37.69	-1.43	-3.79%
<i>Daily 24-Hour Average Concentration (ppb)</i>			
Minimum ^C	11.43	-0.59	-5.16%
Maximum ^C	47.71	-1.60	-3.35%
Average	28.30	-0.82	-2.90%
Median	28.40	-0.86	-3.03%
Population-Weighted Average ^D	28.76	-0.72	-2.50%
<i>Daily 12-Hour Average Concentration (ppb)</i>			
Minimum ^C	16.49	-1.10	-6.67%
Maximum ^C	75.90	-2.89	-3.81%
Average	34.46	-1.53	-4.44%
Median	34.52	-1.13	-3.27%
Population-Weighted Average ^D	36.97	-1.35	-3.65%

^A These ozone metrics are calculated at the CAPMS grid-cell level for use in health effects estimates based on the results of enhanced spatial interpolation. Except for the daily 24-hour average, these ozone metrics are calculated over relevant time periods during the daylight hours (7 am to 7 pm) of the “ozone season,” i.e., May through September. For the 8-hour average, the relevant time period is 9 am to 5 pm, and, for the 5-hour maximum, it is 10 am to 3 pm.

^B The change is defined as the control case value minus the base case value. The percent change is the “Change” divided by the “2030 Base Case,” and then multiplied by 100 to convert the value to a percentage.

^C The base case minimum (maximum) is the value for the CAPMS grid cell with the lowest (highest) value.

^D Calculated by summing the product of the projected 2030 CAPMS grid-cell population and the estimated 2030 CAPMS grid-cell seasonal ozone concentration, and then dividing by the total population. The resulting value is then multiplied by 100 to convert the value to a percentage.

Table VII-3. Summary of UAM-V Derived Ozone Air Quality Metrics Due to HD Engine/Diesel Fuel Standards for Welfare Benefits Endpoints: Eastern U.S.

<i>Statistic^A</i>	<i>2030 Base Case</i>	<i>Change^B</i>	<i>Percent Change^B</i>
<i>Sum06 (ppb)</i>			
Minimum ^C	0.00	0.00	0.00%
Maximum ^C	53.36	-29.10	-54.54%
Average	21.66	-16.91	-78.05%
Median	23.44	-19.50	-83.19%
Population-Weighted Average ^D	23.19	-11.19	-48.26%

^A SUM06 is defined as the cumulative sum of hourly ozone concentrations over 0.06 ppm (or 60 ppb) that occur during daylight hours (from 8am to 8pm) in the months of May through September. It is calculated at the county level for use in agricultural benefits based on the results of enhanced spatial interpolation.

^B The change is defined as the control case value minus the base case value. The percent change is the “Change” divided by the “2030 Base Case,” which is then multiplied by 100 to convert the value to a percentage.

^C The base case minimum (maximum) is the value for the county level observation with the lowest (highest) concentration.

^D Calculated by summing the product of the projected 2030 county population and the estimated 2030 county level ozone concentration, and then dividing by the total population. The resulting value is then multiplied by 100 to convert the value to a percentage.

2. PM Air Quality Estimates

We use the previously described emissions inputs with a national-scale version of the Regulatory Model System for Aerosols and Deposition (REMSAD) to estimate PM air quality in the contiguous U.S. REMSAD was developed as an extension of the episodic UAM-V regional model. Like UAM-V, REMSAD is a three-dimensional grid-based Eulerian air quality model designed to estimate annual particulate concentrations and deposition over large spatial scales (e.g., over the contiguous U.S.). Consideration of the different processes that affect primary (directly emitted) and secondary (formed by atmospheric processes) PM at the regional scale in different locations is fundamental to understanding and assessing the effects of proposed pollution control measures that affect ozone, PM and deposition of pollutants to the surface.^f Because it accounts for spatial and temporal variations as well as differences in the reactivity of emissions, REMSAD is useful for evaluating the impacts of the HD Engine/Diesel Fuel rule on U.S. PM concentrations. Our analysis applies the modeling system to the entire U.S. for a base-year of 1996 and for two future-year scenarios: a 2030 base case and a 2030 HD Engine/Diesel Fuel control scenario.

^f Given the potential impact of the HD Engine/Diesel Fuel rule on secondarily formed particles it is important to employ a Eulerian model such as REMSAD. The impact of secondarily formed pollutants typically involves primary precursor emissions from a multitude of widely dispersed sources, and chemical and physical processes of pollutants that are best addressed using an air quality model that employs an Eulerian grid model design.

REMSAD was peer-reviewed in 1999 for EPA as reported in “*Scientific Peer-Review of the Regulatory Modeling System for Aerosols and Deposition.*” Earlier versions of REMSAD have been employed for the EPA’s Prospective 812 Report to Congress and for EPA’s Analysis of the Acid Deposition and Ozone Control Act (Senate Bill 172). Version 4.1 of REMSAD was employed for this analysis and is fully described in the air quality technical support documents (US EPA, 2000).

REMSAD simulates every hour of every day of the year and, thus, requires a variety of input files that contain information pertaining to the modeling domain and simulation period. These include gridded, 3-hour average emissions estimates and meteorological fields, initial and boundary conditions, and land-use information. As applied to the contiguous U.S., the model segments the area within the region into square blocks called grids (roughly equal in size to counties), each of which has several layers of air conditions. Using this data, REMSAD generates predictions of 3-hour average PM concentrations for every grid. We then calculated daily and seasonal PM air quality metrics as inputs to the health and welfare C-R functions of the benefits analysis. The following sections provide a more detailed discussion of each of the steps in this evaluation and a summary of the results.

a. Modeling Domain

As shown in Figure VII-3, the modeling domain encompasses the contiguous 48 States. The domain extends from 126 degrees west longitude to 66 degrees west longitude, and from 24 degrees north latitude to 52 degrees north latitude. The model contains horizontal grid-cells across the model domain of roughly 36 km by 36 km. There are 8 vertical layers of atmospheric conditions with the top of the modeling domain at roughly 16,000 meters. The 36 by 36 km horizontal grid results in a 120 by 92 grid (or 10,080 grid-cells) for each vertical layer. Figure VII-4 illustrates the horizontal grid-cells for Maryland and surrounding areas.

b. Simulation Periods

For use in this benefits analysis, the simulation periods modeled by REMSAD included separate full-year application for 2030 base case and control scenarios with emissions inventories described in Chapter III.

c. Model Inputs

REMSAD requires a variety of input files that contain information pertaining to the modeling domain and simulation period. These include gridded, 3-hour average emissions estimates and meteorological fields, initial and boundary conditions, and land-use information. Separate emissions inventories were prepared for the 1996 base-year and each of the 2030 future-year base case and control scenarios. All other inputs were specified for the 1996 base-year model application and remained unchanged for each future-year modeling scenario.

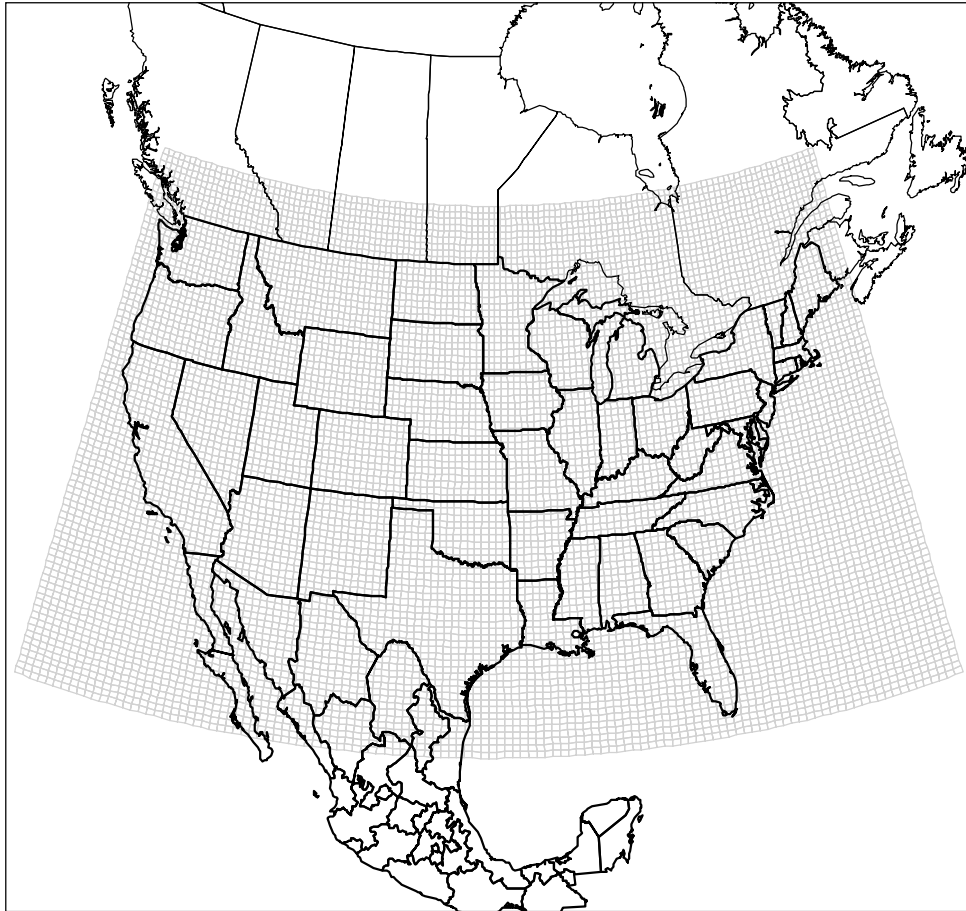


Figure VII-3. REMSAD Modeling Domain for Continental U.S.

Note: Gray markings define individual grid-cells in the REMSAD model.

Similar to UAM-V, REMSAD requires detailed emissions inventories containing

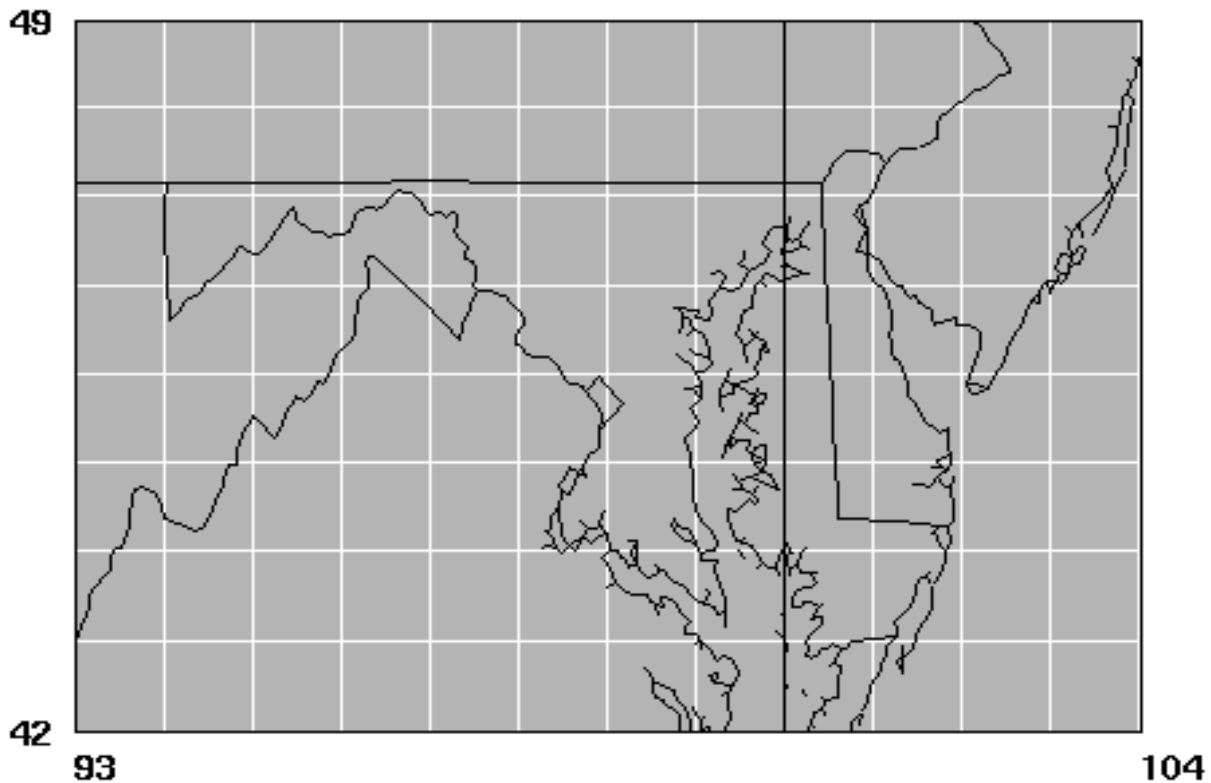


Figure VII-4. Example of REMSAD 36 x 36km Grid-cells for Maryland Area

Note: Gray markings define individual grid-cells in the REMSAD model.

temporally allocated emissions for each grid-cell in the modeling domain for each species being simulated. The previously described annual emission inventories reflecting 2030 base case and control scenarios were preprocessed into model-ready inputs through the Emissions Preprocessing System, Version 2.5 (EPS2.5). The core of EPS2.5 is a series of FORTRAN modules that incorporate spatial, temporal, and chemical resolution into an emissions inventory for use in a photochemical model. Meteorological inputs reflecting 1996 conditions across the contiguous U.S. were derived from Version 5 of the Mesoscale Model (MM5). These inputs included horizontal wind components (i.e., speed and direction), temperature, moisture, vertical diffusion rates, and rainfall rates for each grid cell in each vertical layer. Details of the annual 1996 MM5 modeling are provided in MCNC (2000).

Initial species concentrations and lateral boundary conditions were specified to approximate background concentrations of the species; for the lateral boundaries the concentrations varied (decreased parabolically) with height. These background concentrations are provided in the air quality modeling TSD (US EPA, 2000a). Land use information was obtained from the U.S. Geological Survey database at 10 km resolution.

d. Converting REMSAD Outputs to Benefits Inputs and Model Performance

REMSAD generates predictions of hourly PM concentrations for every grid. The particulate matter species modeled by REMSAD include a primary coarse fraction (corresponding to PM in the 2.5 to 10 micron size range), a primary fine fraction (corresponding to PM less than 2.5 microns in diameter), and several secondary particles (e.g., sulfates, nitrates, and organics). $PM_{2.5}$ is calculated as the sum of the primary fine fraction and all of the secondarily-formed particles. These hourly predictions form the basis for direct calculation of daily and annual PM air quality metrics (i.e., annual mean PM concentration) as inputs to the health and welfare C-R functions of the benefits analysis. In addition, the speciated predictions from REMSAD are employed as inputs to a post-processing module that estimates atmospheric visibility, as discussed later in Section B-3 (US EPA, 2000a).

We modeled 1996 and 2030 base and HD Engine/Diesel Fuel control scenarios. The 2030 modeling is used in this benefits assessment. The goal of the 1996 base year modeling was to reproduce the atmospheric processes resulting in formation and dispersion of $PM_{2.5}$ across the U.S. and to evaluate operational model performance for $PM_{2.5}$ and its related speciated components (e.g., sulfate, nitrate, elemental carbon) in order to estimate the ability of the modeling system to replicate base year concentrations.

This evaluation is comprised principally of statistical assessments of model versus observed pairs. The robustness of any evaluation is directly proportional to the amount and quality of the ambient data available for comparison. Unfortunately, there are few $PM_{2.5}$ monitoring networks with available data for evaluation of the HD Engine/Diesel Fuel PM modeling. Critical limitations of the existing databases are a lack of urban monitoring sites with speciated measurements and poor geographic representation of ambient concentration in the East. The largest available ambient database for 1996 comes from the **I**nteragency **M**onitoring of **P**ROtected **V**isual **E**nvironments (IMPROVE) network. IMPROVE is a cooperative visibility monitoring effort between EPA, federal land management agencies, and state air agencies. Data is collected at Class I areas across the United States mostly at National Parks, National Wilderness Areas, and other protected pristine areas (IMPROVE 2000). There were approximately 60 IMPROVE sites across the nation that had complete annual data in 1996. Forty two of these sites were in the Western U.S. and 18 sites were in the Eastern U.S.

A comparison of predicted versus observed annual average $PM_{2.5}$ concentrations at the IMPROVE sites indicates that $PM_{2.5}$ is underpredicted by about 25% on a nationwide aggregated basis. Most of the underprediction occurs at the Western sites where the overall underprediction is about 35%. However, in the East, ambient $PM_{2.5}$ is overpredicted by about 10%. In addition, model performance was examined for the five component species of $PM_{2.5}$ (sulfate, nitrate, elemental carbon, organic carbon, and other (crustal) fine PM). The results indicate that the performance for both sulfate and elemental carbon was similar to that of $PM_{2.5}$. That is, sulfate and elemental carbon were slightly overpredicted in the East and slightly underpredicted in the West. The performance for nitrate, crustal PM, and organic aerosols was not as good as the performance for the other species. Specifically, nitrate and crustal PM were overpredicted in the East, and organic carbon was underpredicted domainwide.

It should be noted that PM_{2.5} modeling is an evolving science. There have been few regional or national scale model applications for primary and secondary PM. In fact, this is one of the first nationwide applications of a full chemistry Eulerian grid model for the purpose of estimating annual average concentrations of PM_{2.5} and its component species. Also, unlike ozone modeling, there is essentially no database of past performance statistics against which to measure the performance of the HD Engine/Diesel Fuel PM modeling. Given the state of the science relative to PM modeling, it is inappropriate to judge PM model performance using criteria derived for other pollutants, like ozone. Still, the performance of the HD Engine/Diesel Fuel PM modeling is very encouraging, especially considering that the results may be limited by our current knowledge of PM science and chemistry, and by the emissions inventories for primary PM and secondary PM precursor pollutants. Further details of the model performance for PM can be found in the air quality modeling Technical Support Document (US EPA 2000).

e. PM Air Quality Results

Table VII-4 provides a summary of the predicted ambient PM₁₀ and PM_{2.5} concentrations from REMSAD for the 2030 base case and changes associated with HD Engine/Diesel Fuel control scenario. The REMSAD results indicate that the predicted change in PM concentrations is composed almost entirely of reductions in fine particulates (PM_{2.5}) with little or no reduction in coarse particles (PM₁₀ less PM_{2.5}). Therefore, the observed changes in PM₁₀ are composed primarily of changes in PM_{2.5}. In addition to the standard frequency statistics (e.g., minimum, maximum, average, median), Table VII-4 provides the population-weighted average which better reflects the baseline levels and predicted changes for more populated areas of the nation. This measure, therefore, will better reflect the potential benefits of these predicted changes through exposure changes to these populations. As shown, the average annual mean concentrations of PM_{2.5} across all U.S. grid-cells declines by roughly 3.1 percent, or 0.27 $\mu\text{g}/\text{m}^3$. The population-weighted average mean concentration declined by 4.4 percent, or 0.65 $\mu\text{g}/\text{m}^3$, which is much larger in absolute terms than the spatial average. This indicates the HD Engine/Diesel Fuel rule generates greater absolute air quality improvements in more populated, urban areas.

Table VII-5 provides information on the 2030 populations that will experience improved PM air quality. There are significant populations that live in areas with meaningful reductions in annual mean PM_{2.5} concentrations resulting from the HD Engine/Diesel Fuel rule. As shown, just over 15 percent of the 2030 U.S. population are predicted to experience reductions of greater than 1 $\mu\text{g}/\text{m}^3$. Furthermore, almost 33 percent of the 2030 U.S. population will benefit from reductions in annual mean PM_{2.5} concentrations of greater than 0.75 $\mu\text{g}/\text{m}^3$ and slightly over 60 percent will live in areas with reductions of greater than 0.5 $\mu\text{g}/\text{m}^3$. This information indicates how widespread the improvements in PM air quality are expected to be and the large populations that will benefit from these improvements.

Table VII-4. Summary of 2030 Base Case PM Air Quality and Changes Due to HD Engine/Diesel Fuel Standards

<i>Statistic</i>	<i>2030 Base Case</i>	<i>Change^A</i>	<i>Percent Change</i>
<i>PM₁₀</i>			
Minimum Annual Mean ($\mu\text{g}/\text{m}^3$) ^B	1.52	-0.03	-2.0%
Maximum Annual Mean ($\mu\text{g}/\text{m}^3$) ^B	65.68	-1.39	-2.1%
Average Annual Mean ($\mu\text{g}/\text{m}^3$)	10.31	-0.28	-2.4%
Median Annual Mean ($\mu\text{g}/\text{m}^3$)	8.15	-0.18	-2.3%
Population-Weighted Average Annual Mean ($\mu\text{g}/\text{m}^3$) ^C	21.70	-0.66	-3.1%
<i>PM_{2.5}</i>			
Minimum Annual Mean ($\mu\text{g}/\text{m}^3$) ^B	1.19	-0.03	-2.4%
Maximum Annual Mean ($\mu\text{g}/\text{m}^3$) ^B	39.55	-1.35	-3.4%
Average Annual Mean ($\mu\text{g}/\text{m}^3$)	7.87	-0.27	-3.1%
Median Annual Mean ($\mu\text{g}/\text{m}^3$)	5.96	-0.17	-3.0%
Population-Weighted Average Annual Mean ($\mu\text{g}/\text{m}^3$) ^C	14.85	-0.65	-4.4%

^A The change is defined as the control case value minus the base case value.

^B The base case minimum (maximum) is the value for the populated grid-cell with the lowest (highest) annual average. The change relative to the base case is the observed change for the populated grid-cell with the lowest (highest) annual average in the base case.

^C Calculated by summing the product of the projected 2030 grid-cell population and the estimated 2030 PM concentration, for that grid-cell and then dividing by the total population in the 48 contiguous States.

Table VII-5. Distribution of $PM_{2.5}$ Air Quality Improvements Over 2030 Population Due to HD Engine/Diesel Fuel Standards

Change in Annual Mean $PM_{2.5}$ Concentrations ($\mu\text{g}/\text{m}^3$)	2030 Population	
	Number (millions)	Percent (%)
$0 > \Delta PM_{2.5} \text{ Conc} \leq 0.25$	43.0	11.2%
$0.25 > \Delta PM_{2.5} \text{ Conc} \leq 0.5$	95.0	27.5%
$0.5 > \Delta PM_{2.5} \text{ Conc} \leq 0.75$	94.9	27.5%
$0.75 > \Delta PM_{2.5} \text{ Conc} \leq 1.0$	60.5	17.5%
$1.0 > \Delta PM_{2.5} \text{ Conc} \leq 1.25$	23.4	6.8%
$1.25 > \Delta PM_{2.5} \text{ Conc} \leq 1.5$	20.9	6.1%
$1.5 > \Delta PM_{2.5} \text{ Conc} \leq 1.75$	2.9	0.9%
$\Delta PM_{2.5} \text{ Conc} > 1.75$	5.2	1.5%

^A The change is defined as the control case value minus the base case value.

Table VII-6 provides additional insights on the changes in PM air quality resulting from the HD Engine/Diesel Fuel standards. The information presented previously in Table VII-4 illustrated the absolute and relative changes for different points along the distribution of baseline 2030 PM concentration levels, e.g., the change reflects the lowering of the minimum predicted baseline concentration rather than the minimum predicted change for 2030. The latter is the focus of Table VII-6 as it presents the distribution of predicted changes in both absolute terms (i.e., $\mu\text{g}/\text{m}^3$) and relative terms (i.e., percent) across individual grid-cells. As shown, the absolute reduction in annual mean PM_{10} concentration ranged from a low of $0.02 \mu\text{g}/\text{m}^3$ to a high of $2.18 \mu\text{g}/\text{m}^3$, while the relative reduction ranged from a low of 0.2 percent to a high of 9.9 percent. Alternatively, for mean $PM_{2.5}$, the absolute reduction ranged from 0.02 to $2.13 \mu\text{g}/\text{m}^3$, while the relative reduction ranged from 0.4 to 13.1 percent.

Table VII-6. Summary of Absolute and Relative Changes in PM Air Quality Due to HD Engine/Diesel Fuel Standards

<i>Statistic</i>	<i>PM₁₀ Annual Mean</i>	<i>PM_{2.5} Annual Mean</i>
<i>Absolute Change from 2030 Base Case (μg/m³)^A</i>		
Minimum	-0.02	-0.02
Maximum	-2.18	-2.13
Average	-0.28	-0.27
Median	-0.18	-0.17
Population-Weighted Average ^C	-0.66	-0.65
<i>Relative Change from 2030 Base Case (%)^B</i>		
Minimum	-0.17%	-0.38%
Maximum	-9.87%	-13.14%
Average	-2.35%	-3.08%
Median	-2.29%	-2.97%
Population-Weighted Average ^C	-3.08%	-4.36%

^A The absolute change is defined as the control case value minus the base case value for each county.

^B The relative change is defined as the absolute change divided by the base case value, or the percentage change, for each gridcell. The information reported in this section does not necessarily reflect the same gridcell as is portrayed in the absolute change section.

^C Calculated by summing the product of the projected 2030 gridcell population and the estimated 2030 gridcell PM absolute/relative measure of change, and then dividing by the total population in the 48 contiguous states.

3. Visibility Degradation Estimates

Visibility degradation is often directly proportional to decreases in light transmittal in the atmosphere. Scattering and absorption by both gases and particles decrease light transmittance. To quantify changes in visibility, our analysis computes a light-extinction coefficient, based on the work of Sisler (1996), which shows the total fraction of light that is decreased per unit distance. This coefficient accounts for the scattering and absorption of light by both particles and gases, and accounts for the higher extinction efficiency of fine particles compared to coarse particles. Fine particles with significant light-extinction efficiencies include sulfates, nitrates, organic carbon, elemental carbon (soot), and soil (Sisler, 1996).

Based upon the light-extinction coefficient, we also calculated a unitless visibility index, called a “deciview,” which is used in the valuation of visibility. The deciview metric provides a linear scale for perceived visual changes over the entire range of conditions, from clear to hazy. Under many scenic conditions, the average person can generally perceive a change of one deciview. The higher the deciview value, the worse the visibility. Thus, an improvement in visibility is a decrease in deciview value.

Table VII-7 provides the distribution of visibility improvements across 2030 population resulting from the HD Engine/Diesel Fuel rule. The majority of the 2030 U.S. population live in areas with predicted improvement in annual average visibility of between 0.4 to 0.6 deciviews resulting from the HD Engine/Diesel Fuel rule. As shown, almost 20 percent of the 2030 U.S. population are predicted to experience improved annual average visibility of greater than 0.6 deciviews. Furthermore, roughly 70 percent of the 2030 U.S. population will benefit from reductions in annual average visibility of greater than 0.4 deciviews. The information provided in Table VII-7 indicates how widespread the improvements in visibility are expected to be and the share of populations that will benefit from these improvements.

Because the visibility benefits analysis distinguishes between general regional visibility degradation and that particular to Federally-designated Class I areas (i.e., national parks, forests, recreation areas, wilderness areas, etc.), we separated estimates of visibility degradation into “residential” and “recreational” categories. The estimates of visibility degradation for the “recreational” category apply to Federally-designated Class I areas, while estimates for the “residential” category apply to non-Class I areas. Deciview estimates are estimated using outputs from REMSAD for the 2030 base case and HD Engine/Diesel Fuel control scenarios.

Table VII-7. Distribution of Populations Experiencing Visibility Improvements in 2030 Due to HD Engine/Diesel Fuel Standards

<i>Improvements in Visibility^A</i> <i>(annual average deciviews)</i>	<i>2030 Population</i>	
	<i>Number (millions)</i>	<i>Percent (%)</i>
$0 > \Delta \text{Deciview} \leq 0.2$	12.1	3.5%
$0.2 > \Delta \text{Deciview} \leq 0.4$	87.4	25.3%
$0.4 > \Delta \text{Deciview} \leq 0.6$	179.7	51.9%
$0.6 > \Delta \text{Deciview} \leq 0.8$	54.5	15.8%
$0.8 > \Delta \text{Deciview} \leq 1.0$	10.7	3.1%
$\Delta \text{Deciview} > 1.0$	1.5	0.4%

^A The change is defined as the control case deciview level minus the base case deciview level.

a. Residential Visibility Improvements

Air quality modeling results predict that the HD Engine/Diesel Fuel rule will create improvements in visibility through the country. In Table VII-8, we summarize residential visibility improvements across the Eastern and Western U.S. in 2030. The baseline annual average visibility for all U.S. counties is 14.8 deciviews. The mean improvement across all U.S. counties is 0.28 deciviews, or almost 2 percent. In urban areas with a population of 250,000 or more (i.e., 1,209 out of 5,147 counties), the mean improvement in annual visibility was 0.39

deciviews and ranged from 0.05 to 1.08 deciviews. In rural areas (i.e., 3,938 counties), the mean improvement in visibility was 0.25 deciviews in 2030 and ranged from 0.02 to 0.94 deciviews.

On average, the Eastern U.S. experienced slightly larger absolute but smaller relative improvements in visibility than the Western U.S. from the HD Engine/Diesel Fuel reductions. In Eastern U.S., the mean improvement was 0.34 deciviews from an average baseline of 19.32 deciviews. Western counties experienced a mean improvement of 0.21 deciviews from an average baseline of 9.75 deciviews projected in 2030. Overall, the data suggest that the HD Engine/Diesel Fuel rule has the potential to provide widespread improvements in visibility for 2030.

Table VII-8. Summary of 2030 Baseline Visibility and Changes by Region: Residential (Annual Average Deciviews)

<i>Regions^A</i>	<i>2030 Base Case</i>	<i>Change^B</i>	<i>Percent Change</i>
Eastern U.S.	19.32	-0.34	-1.7%
Urban	20.88	-0.40	-1.9%
Rural	18.70	-0.32	-1.7%
Western U.S.	9.75	-0.21	-2.1%
Urban	10.58	-0.37	-3.5%
Rural	9.57	-0.18	-1.9%
National, all counties	14.77	-0.28	-1.9%
Urban	17.12	-0.39	-2.3%
Rural	14.06	-0.25	-1.8%

^A Eastern and Western regions are separated by 100 degrees north longitude. Background visibility conditions differ by region.

^B An improvement in visibility is a decrease in deciview value. The change is defined as the HD Engine/Diesel Fuel control case deciview level minus the basecase deciview level.

b. Recreational Visibility Improvements

In Table VII-9, we summarize recreational visibility improvements by region in 2030 in Federal Class I areas. These recreational visibility regions are shown in Figure VII-5. As shown, the national improvement in visibility for these areas is 2.4 percent, or 0.34 deciviews. Predicted relative visibility improvements are the largest in the Western U.S. as shown for California (4.9%), and the Southwest (2.4%), the Northwest (2.3%), and the Rocky Mountain (1.9%). Although Federal Class I areas in the Southeast region are predicted to have the second largest absolute improvement of 0.42 deciviews, it reflects only a 1.6 percent change from 2030 baseline visibility of 25.44 deciviews. The Northeast/Midwest region was predicted to have the smallest relative visibility improvement at 1.2 percent, or 0.25 deciview decline from a baseline of 21.25 deciviews.

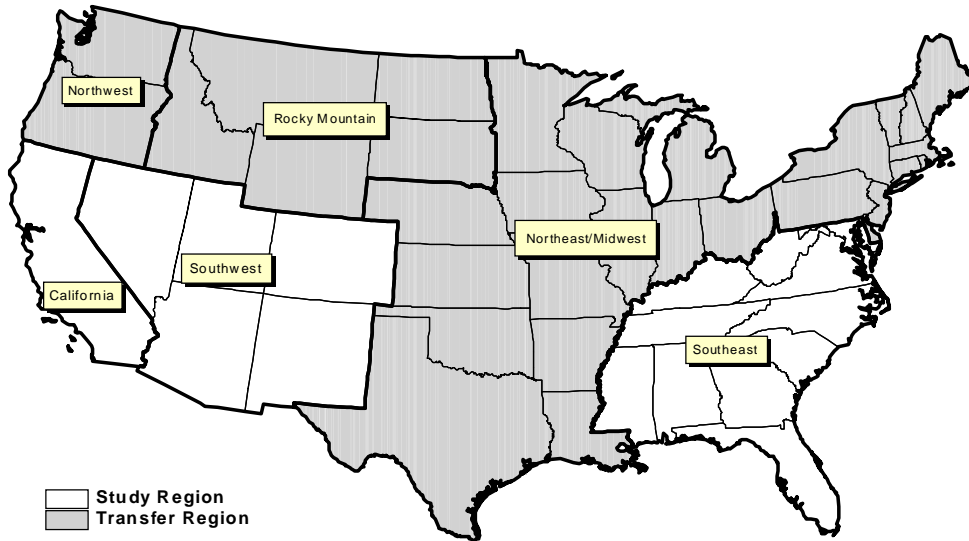


Figure VII-5. Recreational Visibility Regions for Continental U.S.

Table VII-9. Summary of 2030 Baseline Visibility and Changes by Region: Recreational (Annual Average Deciviews)

<i>Class I Visibility Regions^A</i>	<i>2030 Base Case</i>	<i>Change^B</i>	<i>Percent Change</i>
Southeast	25.44	-0.42	-1.6%
Southwest	8.90	-0.21	-2.4%
California	12.21	-0.60	-4.9%
Northeast/Midwest	21.25	-0.25	-1.2%
Rocky Mountain	12.54	-0.24	-1.9%
Northwest	15.80	-0.36	-2.3%
National Average (unweighted)	14.38	-0.34	-2.4%

^A Regions are pictured in Figure VI-5 and are defined in the technical support document (see Abt Associates, 2000).

^B An improvement in visibility is a decrease in deciview value. The change is defined as the HD Engine/Diesel Fuel control case deciview level minus the basecase deciview level.

Note: Study regions were represented in the Chestnut and Rowe (1990a, 1990b) studies used in evaluating the benefits of visibility improvements, while transfer regions used extrapolated study results.

4. Nitrogen Deposition Estimates

This section presents the methods and results of estimating the potential reductions in airborne nitrogen deposition loadings to estuaries associated with the HD Engine/Diesel Fuel rule. A sampling of 12 estuaries (10 East Coast and 2 Gulf Coast estuaries) were used for this analysis because of the availability of necessary data and their potential representativeness. For each estuary, we completed the following steps as part of this analysis:

- n. Baseline loadings of atmospherically supplied nitrogen were obtained from data provided in Valigura, et al. (1996) and from local offices of the Chesapeake Bay Program and the National Estuary Program;
- o. Deposition from atmospheric emissions were divided into local and regional areas that contribute to airborne nitrogen deposition;
- p. Deposition coefficients, which relate NO_x emission changes from a source region to nitrogen deposition changes at a receptor region, were derived for local and regional contributors; and
- q. Changes in nitrogen deposition loadings were estimated by multiplying NO_x emission changes for the local and regional contributing areas by the appropriate deposition coefficients.

For five of the twelve estuaries, estimates of both direct deposition to the tidal waters and indirect deposition to the entire watershed were available from the literature. For the remaining seven estuaries, only direct deposition estimates were available. Therefore, to obtain indirect deposition estimates where missing, we used RADM-derived nitrogen flux for the watershed (Dennis, 1997). This analysis assumes that 10 percent of nitrogen deposited onto the watershed is delivered via export (pass-through) to the estuary.[§] This calculated indirect deposition value is then added to the direct deposition value obtained from the literature to arrive at the total load from atmospheric deposition.

As stated in Step D above, the nitrogen deposition results are heavily dependent upon the deposition coefficients that estimate the impact of NO_x emission changes on nitrogen deposition loadings. For this analysis, two deposition coefficients, an *alpha* and a *beta*, were developed for each estuary. The alpha coefficient relates local emissions to deposition and the beta coefficient relates regional emissions to deposition. These coefficients are calculated for each estuary using deposition outputs from RADM as employed for the final NO_x SIP Call (US EPA, 1998b). More detail on this approach and results may be found in Pechan-Avanti (2000).

[§] This assumption is consistent with reported case studies such as Valiela et al., 1997. These authors report that 89 percent of atmospherically deposited nitrogen was retained by the watershed of Waquoit Bay, suggesting an 11 percent pass through factor.

Table VII-10 provides a summary of the baseline deposition and change in nitrogen deposition estimates for the selected estuaries as a result of the HD Engine/Diesel Fuel rule. As shown, implementation results in roughly a 21 percent reduction in the average annual deposition across these estuaries. These predicted reductions range from a low of 17.2 percent for Delaware Inland Bay to highs of 21.6 percent for Long Island Sound and 24 percent for Tampa Bay.

Table VII-10. Summary of 2030 Nitrogen Deposition in Selected Estuaries and Changes Due to HD Engine/Diesel Fuel Rule (million kg/year)

<i>Estuary</i>	<i>2030 Base Case</i>	<i>Change^A</i>	<i>Percent Change</i>
Albemarle/Pamlico Sound	7.66	-1.64	-21.4%
Cape Cod Bay	2.98	-0.61	-20.4%
Chesapeake Bay	12.04	-2.46	-20.5%
Delaware Bay	2.56	-0.49	-19.4%
Delaware Inland Bays	0.32	-0.05	-17.2%
Gardiners Bay	0.90	-0.19	-20.8%
Hudson River/Raritan Bay	3.07	-0.61	-19.9%
Long Island Sound	4.51	-0.97	-21.6%
Massachusetts Bay	1.03	-0.21	-20.3%
Narragansett Bay	0.89	-0.18	-20.5%
Sarasota Bay	0.24	-0.05	-20.6%
Tampa Bay	1.46	-0.35	-24.0%
All Selected Estuaries	37.64	-7.82	-20.8%

^A Change is defined here as the emissions level after implementing the HD Engine/Diesel Fuel rule minus the base case emissions.

C. Benefit Analysis

1. Methods for Estimating Benefits from Air Quality Improvements

Environmental and health economists have a number of methods for estimating the economic value of improvements in (or deterioration of) environmental quality. The method used in any given situation depends on the nature of the effect and the kinds of data, time, and resources that are available for investigation and analysis. This section provides an overview of the methods we selected to monetize the benefits included in this HD Engine/Diesel Fuel RIA.

We note at the outset that EPA rarely has the time or resources to perform extensive new research to measure economic benefits for individual rulemakings. As a result, our estimates are based on the best available methods of benefits transfer. Benefits transfer is the science and art of adapting primary benefits research from similar contexts to obtain the most accurate measure of benefits for the environmental quality change under analysis. Where appropriate, adjustments are made for the level of environmental quality change, the sociodemographic and economic characteristics of the affected population, and other factors in order to improve the accuracy and robustness of benefits estimates.

In general, economists tend to view an individual's willingness-to-pay (WTP) for a improvement in environmental quality as the appropriate measure of the value of a risk reduction. An individual's willingness-to-accept (WTA) compensation for not receiving the improvement is also a valid measure. However, WTP is generally considered to be a more readily available and conservative measure of benefits. Adoption of WTP as the measure of value implies that the value of environmental quality improvements is dependent on the individual preferences of the affected population and that the existing distribution of income (ability to pay) is appropriate.

For many goods, WTP can be observed by examining actual market transactions. For example, if a gallon of bottled drinking water sells for one dollar, it can be observed that at least some persons are willing to pay one dollar for such water. For goods not exchanged in the market, such as most environmental "goods," valuation is not as straightforward. Nevertheless, a value may be inferred from observed behavior, such as sales and prices of products that result in similar effects or risk reductions, (e.g., non-toxic cleaners or bike helmets). Alternatively, surveys may be used in an attempt to directly elicit WTP for an environmental improvement.

One distinction in environmental benefits estimation is between use values and non-use values. Although no general agreement exists among economists on a precise distinction between the two (see Freeman, 1993), the general nature of the difference is clear. Use values are those aspects of environmental quality that affect an individual's welfare more or less directly. These effects include changes in product prices, quality, and availability, changes in the quality of outdoor recreation and outdoor aesthetics, changes in health or life expectancy, and the costs of actions taken to avoid negative effects of environmental quality changes.

Non-use values are those for which an individual is willing to pay for reasons that do not relate to the direct use or enjoyment of any environmental benefit, but might relate to existence values and bequest values. Non-use values are not traded, directly or indirectly, in markets. For this reason, the measurement of non-use values has proved to be significantly more difficult than the measurement of use values. The air quality changes produced by the final HD Engine/Diesel Fuel rule cause changes in both use and non-use values, but the monetary benefit estimates are almost exclusively for use values.

More frequently than not, the economic benefits from environmental quality changes are not traded in markets, so direct measurement techniques can not be used. Avoided cost methods are ways to estimate the costs of pollution by using the expenditures made necessary by pollution

damage. For example, if buildings must be cleaned or painted more frequently as levels of PM increase, then the appropriately calculated increment of these costs is a reasonable lower bound estimate (under most conditions) of true economic benefits when PM levels are reduced. A variation on the avoided cost method is used to provide an alternative estimate of the benefits of reductions in nitrogen deposition to estuaries (see Sections C.4 and F). Avoided costs methods are also used to estimate some of the health-related benefits related to morbidity, such as hospital admissions (see section D).

Indirect market methods can also be used to infer the benefits of pollution reduction. The most important application of this technique for our analysis is the calculation of the value of a statistical life for use in the estimate of benefits from mortality reductions. There exists no market where changes in the probability of death are directly exchanged. However, people make decisions about occupation, precautionary behavior, and other activities associated with changes in the risk of death. By examining these risk changes and the other characteristics of people's choices, it is possible to infer information about the monetary values associated with changes in mortality risk (see Section D). For measurement of health benefits, this analysis captures the WTP for most use and non-use values, with the exception of the value of avoided hospital admissions, which only captures the avoided cost of illness because no WTP values were available in the published literature.

The most direct way to measure the economic value of air quality changes is in cases where the endpoints have market prices. For the final rule, this can only be done for effects on commercial agriculture and forestry. Well-established economic modeling approaches are used to predict price changes that result from predicted changes in agricultural and forestry outputs. Consumer and producer surplus measures can then be developed to give reliable indications of the benefits of changes in ambient air quality for these categories (see Section E).

Estimating benefits for visibility and ecosystem services is a more difficult and less precise exercise because the endpoints are not directly or indirectly valued in markets. For example, the loss of a species of animal or plant from a particular habitat does not have a well-defined price. The contingent valuation (CV) method has been employed in the economics literature to value endpoint changes for both visibility and ecosystem functions (Chestnut and Dennis, 1997). The CV method values endpoints by using carefully structured surveys to ask a sample of people what amount of compensation is equivalent to a given change in environmental quality. There is an extensive scientific literature and body of practice on both the theory and technique of CV. EPA believes that well-designed and well-executed CV studies are valid for estimating the benefits of air quality regulation.^h

^hConcerns about the reliability of value estimates from CV studies arose because research has shown that bias can be introduced easily into these studies if they are not carefully conducted. Accurately measuring WTP for avoided health and welfare losses depends on the reliability and validity of the data collected. There are several issues to consider when evaluating study quality, including but not limited to 1) whether the sample estimates of WTP are representative of the population WTP; 2) whether the good to be valued is comprehended and accepted by the respondent; 3) whether the WTP elicitation format is designed to minimize strategic responses; 4) whether WTP is sensitive to respondent familiarity with the good, to the size of the change in the good, and to income; 5) whether

Our analysis accounts for expected growth in real income over time. Economic theory argues that WTP for most goods (such as environmental protection) will increase if real incomes increase. There is substantial empirical evidence that the income elasticity¹ of WTP for health risk reductions is positive, although there is uncertainty about its exact value. Thus, as real income increases the WTP for environmental improvements also increases. While many analyses assume that the income elasticity of WTP is unit elastic (i.e., ten percent higher real income level implies a ten percent higher WTP to reduce risk changes), empirical evidence suggests that income elasticity is substantially less than one and thus relatively inelastic. As real income rises, the WTP value also rises but at a slower rate than real income.

The effects of real income changes on WTP estimates can influence benefit estimates in two different ways: (1) through real income growth between the year a WTP study was conducted and the year for which benefits are estimated, and (2) through differences in income between study populations and the affected populations at a particular time. Empirical evidence of the effect of real income on WTP gathered to date is based on studies examining the former. The Environmental Economics Advisory Committee (EEAC) of the SAB advised EPA to adjust WTP for increases in real income over time, but not to adjust WTP to account for cross-sectional income differences “because of the sensitivity of making such distinctions, and because of insufficient evidence available at present” (EPA-SAB-EEAC-00-013).

Based on a review of the available income elasticity literature, we adjust the valuation of human health benefits upward to account for projected growth in real U.S. income. Faced with a dearth of estimates of income elasticities derived from time-series studies, we applied estimates derived from cross-sectional studies in our analysis. Details of the procedure can be found in Kleckner and Neumann (1999). An abbreviated description of the procedure we used to account for WTP for real income growth between 1990 and 2030 is presented below.

Reported income elasticities suggest that the severity of a health effect is a primary determinant of the strength of the relationship between changes in real income and WTP. As such, we use different elasticity estimates to adjust the WTP for minor health effects, severe and chronic health effects, and premature mortality. We also expect that the WTP for improved visibility in Class I areas would increase with growth in real income. The elasticity values used to adjust the primary estimate of benefits are presented in Table VII-11. In addition to the primary estimate, we also present the impacts of using different assumed elasticities in Table VII-25.

the estimates of WTP are broadly consistent with other estimates of WTP for similar goods; and 6) the extent to which WTP responses are consistent with established economic principles.

¹Income elasticity is a common economic measure equal to the percentage change in WTP for a one percent change in income.

Table VII-11. Elasticity Values Used to Account for Projected Real Income Growth^A

Benefit Category	Lower Sensitivity Bound	Primary	Upper Sensitivity Bound
Minor Health Effect	0.04	0.14	0.30
Severe and Chronic Health Effects	0.25	0.45	0.60
Premature Mortality	0.08	0.40	1.00
Visibility ^B	--	0.90	--

^A Derivation of these ranges can be found in Kleckner and Neumann (1999) and Chestnut (1997). Cost of Illness (COI) estimates are assigned an adjustment factor of 1.0.

^B No range was applied for visibility because no ranges were available in the current published literature.

Accounting for real income growth over time requires projections of both real gross domestic product (GDP) and populations. For consistency with the emissions and benefits modeling, we use population estimates for the years 2015, 2020, and 2030 as described in Davidson (1999). These population estimates are based on 1990 U.S. Census data and Bureau of Economic Analysis growth projections.^j For the years between 1990 and 2010, we use population estimates provided in Kleckner and Neumann (1999), which were obtained from the US Bureau of Census.^k We use projections of real GDP provided in Kleckner and Neumann (1999) for the years 1990 to 2010.^l We use projections of real GDP (in chained 1996 dollars) provided by Standard and Poor's for the years 2010 to 2024.^m The Standard and Poor's database only provides estimates of real GDP between 1990 and 2024. We were unable to find reliable projections of GDP beyond 2024. As such, we assume that per capita GDP remains constant between 2024 and 2030. This assumption will lead us to under-predict benefits because at least some level of income growth would be projected to occur between the years 2024 and 2030.

Using the method outlined in Kleckner and Neumann (1999), and the population and income data described above, we calculate income growth factors for each of the elasticity

^j US Bureau of Census. Annual Projections of the Total Resident Population, Middle Series, 1999-2010. (Available on the internet at <http://www.census.gov/population/projections/nation/summary/np-t1.txt>)

^k US Bureau of Census. Historic National Population Estimates. (Available on the internet at <http://www.census.gov/population/estimates/nation/poplockest.txt>) and US Bureau of Census. Resident Population Projections of the U.S.; Middle Series. (Available on the internet at <http://www.census.gov/population/estimates/nation/npaltsrs.txt>)

^l US Bureau of Economic Analysis, Table 2A (1992\$). (Available on the internet at <http://www.bea.doc.gov/bea/dn/0897nip2/tab2a.htm>) and US Bureau of Economic Analysis, Economics and Budget Outlook. Note that projections for 2007 to 2010 are based on average GDP growth rates between 1999 and 2007.

^m Standard and Poor's. 2000. "The U.S. Economy: The 25 Year Focus." Winter 2000.

estimates listed in Table VII-11. Benefits for each of the categories (minor health effects, severe and chronic health effects, premature mortality, and visibility) will be adjusted by multiplying the unadjusted benefits by the appropriate adjustment factor. In Table VII-12 we list the estimated factors. Note that for premature mortality, we apply the income adjustment factor *ex post* to the present discounted value of the stream of avoided mortalities occurring over the lag period. Also note that no adjustments will be made to benefits based on the cost-of-illness approach or to work loss days and worker productivity. This assumption will also lead us to under predict benefits since it is likely that increases in real U.S. income would also result in increased cost-of-illness (due, for example, to increases in wages paid to medical workers) and increased cost of work loss days and lost worker productivity (reflecting that if worker incomes are higher, the losses resulting from reduced worker production would also be higher). No adjustments are needed for agricultural and commercial forestry benefits, as these models are based on projections of supply and demand in future years and should already incorporate future changes in real income. The results are presented in section F.

Table VII-12. Adjustment Factors Used to Account for Projected Real Income Growth^A

Benefit Category	Lower Sensitivity Bound	Primary	Upper Sensitivity Bound
Minor Health Effect	1.026	1.095	1.214
Severe and Chronic Health Effects	1.176	1.341	1.482
Premature Mortality	1.053	1.297	1.956
Visibility ^B	--	1.821	--

^A Based on elasticity values reported in Table VII-11, US Census population projections, and projections of real gross domestic product per capita.

^B No range was applied for visibility because no ranges were available in the current published literature.

2. Methods for Describing Uncertainty

In any complex analysis using estimated parameters and inputs from numerous models, there are likely to be many sources of uncertainty.ⁿ This analysis is no exception. As outlined both in this and preceding chapters, there are many inputs used to derive the final estimate of benefits, including emission inventories, air quality models (with their associated parameters and inputs), epidemiological estimates of concentration-response (C-R) functions, estimates of values (both from WTP and cost-of-illness studies), population estimates, income estimates, and

ⁿ It should be recognized that in addition to uncertainty, the annual benefit estimates for the final HD Engine/Diesel Fuel rule presented in this analysis are also inherently variable, due to the truly random processes that govern pollutant emissions and ambient air quality in a given year. Factors such as electricity demand and weather display constant variability regardless of our ability to accurately measure them. As such, the estimates of annual benefits should be viewed as representative of the types of benefits that will be realized, rather than the actual benefits that would occur every year.

estimates of the future state of the world (i.e., regulations, technology, and human behavior). Each of these inputs may be uncertain, and depending on their location in the benefits analysis, may have a disproportionately large impact on final estimates of total benefits. For example, emissions estimates are used in the first stage of the analysis. As such, any uncertainty in emissions estimates will be propagated through the entire analysis. When compounded with uncertainty in later stages, small uncertainties in emission levels can lead to much larger impacts on total benefits. A more thorough discussion of uncertainty can be found in the benefits technical support document (TSD) (Abt Associates, 2000).

Some key sources of uncertainty in each stage of the benefits analysis are:

- Gaps in scientific data and inquiry;
- Variability in estimated relationships, such as C-R functions, introduced through differences in study design and statistical modeling;
- Errors in measurement and projection for variables such as population growth rates;
- Errors due to misspecification of model structures, including the use of surrogate variables, such as using PM_{10} when $PM_{2.5}$ is not available, excluded variables, and simplification of complex functions; and
- Biases due to omissions or other research limitations.

Some of the key uncertainties in the benefits analysis are presented in Table VII-13. Given the wide variety of sources for uncertainty and the potentially large degree of uncertainty about any primary estimate, it is necessary for us to address this issue in several ways. These include qualitative discussions, probabilistic assessments, alternative calculations, and bounding exercises. For some parameters or inputs it may be possible to provide a statistical representation of the underlying uncertainty distribution. For other parameters or inputs, the information necessary to estimate an uncertainty distribution is not available. Even for individual endpoints, there is usually more than one source of uncertainty. This makes it difficult to provide a quantified uncertainty estimate. For example, the C-R function used to estimate avoided premature mortality has an associated standard error which represents the sampling error around the pollution coefficient in the estimated C-R function. It would be possible to report a confidence interval around the estimated incidences of avoided premature mortality based on this standard error. However, this would omit the contribution of air quality changes, baseline population incidences, projected populations exposed, and transferability of the C-R function to diverse locations to uncertainty about premature mortality. Thus, a confidence interval based on the standard error would provide a misleading picture about the overall uncertainty in the estimates. Information on the uncertainty surrounding particular C-R and valuation functions is provided in the benefits TSD for this RIA (Abt Associates, 2000). But, this information should be interpreted within the context of the larger uncertainty surrounding the entire analysis.

Our approach to characterizing model uncertainty is to present a primary estimate of the benefits, based on the best available scientific literature and methods, and to then provide alternative calculations to illustrate the effects of uncertainty about key analytical assumptions. We do not attempt to assign probabilities to these alternative calculations, as we believe this

would only add to the uncertainty of the analysis or present a false picture about the precision of the results. Instead, the reader is invited to examine the impact of applying the different assumptions on the estimate of total benefits. While it is possible to combine all of the alternative calculations with a positive impact on benefits to form a “high” estimate or all of the alternative calculations with a negative impact on benefits to form a “low” estimate, this would not be appropriate because the probability of all of these alternative assumptions occurring simultaneously is extremely low.^o Instead, the alternative calculations are intended to demonstrate the sensitivity of our benefits results to key parameters which may be uncertain. Alternative calculations are presented in Table VII-25.

Many benefits categories, while known to exist, do not have enough information available to provide a quantified or monetized estimate. The uncertainty regarding these endpoints is such that we could determine neither a primary estimate nor a plausible range of values.

Our estimated range of total benefits should be viewed as an approximate result because of the sources of uncertainty discussed above (see Table VII-13). The total benefits estimate may understate or overstate actual benefits of the rule.

In considering the monetized benefits estimates, the reader should remain aware of the many limitations of conducting these analyses mentioned throughout this RIA. One significant limitation of both the health and welfare benefits analyses is the inability to quantify many of the serious effects listed in Table VII-1. For many health and welfare effects, such as PM-related materials damage, reliable C-R functions and/or valuation functions are not currently available. In general, if it were possible to monetize these benefits categories, the benefits estimates presented in this analysis would increase. Unquantified benefits are qualitatively discussed in the health and welfare effects sections. In addition to unquantified benefits, there may also be environmental costs that we are unable to quantify. Several of these environmental cost categories are related to nitrogen deposition, while one category is related to the issue of ultraviolet light. These endpoints are qualitatively discussed in the health and welfare effects sections as well. The net effect of excluding benefit and disbenefit categories from the estimate of total benefits depends on the relative magnitude of the effects.

^o Some recent benefit-cost analyses in Canada and Europe (Holland et al., 1999; Lang et al., 1995) have estimated ranges of benefits by assigning *ad hoc* probabilities to ranges of parameter values for different endpoints. Although this does generate a quantitative estimate of an uncertainty range, the estimated points on these distributions are themselves highly uncertain and very sensitive to the subjective judgements of the analyst. To avoid these subjective judgements, we choose to allow the reader to determine the weights they would assign to alternative estimates.

Table VII-13. Primary Sources of Uncertainty in the Benefit Analysis

<i>1. Uncertainties Associated With Concentration-Response Functions</i>	
-	The value of the ozone- or PM-coefficient in each C-R function.
-	Application of a single C-R function to pollutant changes and populations in all locations.
-	Similarity of future year C-R relationships to current C-R relationships.
-	Correct functional form of each C-R relationship.
-	Extrapolation of C-R relationships beyond the range of ozone or PM concentrations observed in the study.
-	Application of C-R relationships only to those subpopulations matching the original study population.
<i>2. Uncertainties Associated With Ozone and PM Concentrations</i>	
-	Responsiveness of the models to changes in precursor emissions resulting from the control policy.
-	Projections of future levels of precursor emissions, especially ammonia and crustal materials.
-	Model chemistry for the formation of ambient nitrate concentrations.
-	Lack of ozone monitors in rural areas requires extrapolation of observed ozone data from urban to rural areas.
-	Use of separate air quality models for ozone and PM does not allow for a fully integrated analysis of pollutants and their interactions.
-	Full ozone season air quality distributions are extrapolated from a limited number of simulation days.
VI.	Comparison of model predictions of particulate nitrate with observed rural monitored nitrate levels indicates that REMSAD overpredicts nitrate in some parts of the Eastern US and underpredicts nitrate in parts of the Western US.
<i>3. Uncertainties Associated with PM Mortality Risk</i>	
-	No scientific literature supporting a direct biological mechanism for observed epidemiological evidence.
vii.	Direct causal agents within the complex mixture of PM have not been identified.
-	The extent to which adverse health effects are associated with low level exposures that occur many times in the year versus peak exposures.
ii	The extent to which effects reported in the long-term exposure studies are associated with historically higher levels of PM rather than the levels occurring during the period of study.
-	Reliability of the limited ambient PM _{2.5} monitoring data in reflecting actual PM _{2.5} exposures.
<i>4. Uncertainties Associated With Possible Lagged Effects</i>	
-	The portion of the PM-related long-term exposure mortality effects associated with changes in annual PM levels would occur in a single year is uncertain as well as the portion that might occur in subsequent years.
<i>5. Uncertainties Associated With Baseline Incidence Rates</i>	
9.	Some baseline incidence rates are not location-specific (e.g., those taken from studies) and may therefore not accurately represent the actual location-specific rates.
-	Current baseline incidence rates may not approximate well baseline incidence rates in 2030.
j.	Projected population and demographics may not represent well future-year population and demographics.
<i>6. Uncertainties Associated With Economic Valuation</i>	
-	Unit dollar values associated with health and welfare endpoints are only estimates of mean WTP and therefore have uncertainty surrounding them.
xi.	Mean WTP (in constant dollars) for each type of risk reduction may differ from current estimates due to differences in income or other factors.
-	Future markets for agricultural and forestry products are uncertain.
<i>7. Uncertainties Associated With Aggregation of Monetized Benefits</i>	
ii	Health and welfare benefits estimates are limited to the available C-R functions. Thus, unquantified or unmonetized benefits are not included.

D. Assessment of Human Health Benefits

The most significant monetized benefits of reducing ambient concentrations of PM and ozone are attributable to reductions in health risks associated with air pollution. EPA's Criteria Documents for ozone and PM list numerous health effects known to be linked to ambient concentrations of these pollutants (US EPA, 1996a and 1996b). This section describes individual effects and the methods used to quantify and monetize changes in the expected number of incidences of various health effects.

In Section 1, we discuss how we have determined the baseline incidences for the health effects impacted by changes in PM and ozone. In Section 2, we explain how we address the issue of health effects thresholds. In Section 3, we describe how we quantify and value changes in individual health effects. Finally, in Section 4 we present quantified estimates of the reductions in health effects resulting from the HD Engine/Diesel Fuel rule and their associated monetary values.

1. Estimating Baseline Incidences for Health Effects

The epidemiological studies of the association between pollution levels and adverse health effects generally provide a direct estimate of the relationship of air quality changes to the relative risk of a health effect, rather than an estimate of the absolute number of avoided cases. For example, a typical result might be that a 10 $\mu\text{g}/\text{m}^3$ decrease in daily $\text{PM}_{2.5}$ levels might decrease hospital admissions by three percent. The baseline incidence of the health effect is necessary to convert this relative change into a number of cases.

The baseline incidence used in our analyses needs to match the specific population studied. For example, because some mortality studies considered only non-accidental mortality, we adjusted county-specific baseline total mortality rates used in the estimation of PM-related premature mortality to provide a better estimate of county-specific non-accidental mortality. We multiplied each county-specific mortality rate by the ratio of national non-accidental mortality to national total mortality (0.93) (US Centers for Disease Control, 1999a). An additional adjustment was necessary to provide baseline incidences for adults 30 and older for use in the Krewski, et al. (2000) and Pope, et al. (1995) PM mortality C-R functions. We estimated county-specific baseline mortality incidences for this population by applying national age-specific death rates to county-specific age distributions, and adjusting the resulting estimated age-specific incidences so that the estimated total incidences (including all ages) equals the actual county-specific total incidences. We applied this same procedure to develop baseline incidences for adults 25 and older for use in alternative premature mortality estimates based on Harvard Six-City/Krewski, et al. (2000).

County-level incidence rates are not available for other endpoints. We used national incidence rates whenever possible, because these data are most applicable to a national assessment of benefits. However, for some studies, the only available incidence information

comes from the studies themselves; in these cases, incidence in the study population is assumed to represent typical incidence at the national level.

2. Accounting for Potential Health Effect Thresholds

When conducting clinical (chamber) and epidemiological studies, C-R functions may be estimated with or without explicit thresholds. Air pollution levels below the threshold are assumed to have no associated adverse health effects. When a threshold is not assumed, as is often the case in epidemiological studies, any exposure level is assumed to pose a non-zero risk of response to at least one segment of the population.

The possible existence of an effect threshold is a very important scientific question and issue for policy analyses such as this one. In the benefits analyses for some recent RIAs (see the PM NAAQS RIA, the Regional Haze RIA, and the NO_x SIP Call RIA), the low-end estimate of benefits assumed a threshold in PM health effects at 15 µg/m³. However, the SAB subsequently advised EPA that there is currently no scientific basis for selecting a threshold of 15 µg/m³ or any other specific threshold for the PM-related health effects considered in this analysis (EPA-SAB-Council-ADV-99-012, 1999). Therefore, for our benefits analysis, we assume there are no thresholds for modeling health effects. It is not appropriate to adopt a threshold for use in either the primary analysis or any alternative calculations because no adequate scientific evidence exists to support such a calculation. Although not included in the primary analysis, the potential impact of a health effects threshold on avoided incidences of PM-related premature mortality is explored as a key sensitivity analysis and is presented in Appendix VII-A.

3. Quantifying and Valuing Individual Health Endpoints

Quantifiable health benefits of the final HD Engine/Diesel Fuel rule may be related to ozone only, PM only, or both pollutants. Decreased worker productivity is the only health endpoint related to ozone but not PM.^p PM-only health effects include premature mortality, chronic bronchitis, acute bronchitis, upper and lower respiratory symptoms, and work loss days.^q

^p In the benefits analysis for the recent Tier 2/Gasoline Sulfur rule, based on our interpretation of the advice from the SAB (EPA-SAB-COUNCIL-ADV-00-001), we included avoided incidences of chronic asthma in adult males as a primary health endpoint associated with ozone. Recent advice from asthma experts both within and outside the Agency has led us to conclude that while the McDonnell, et al. (1999) study raises concerns about the possibility of a connection, the scientific evidence supporting the relationship between ozone and new incidences of asthma is not sufficient to support its inclusion in our primary analysis. We do, however, include this important endpoint as an alternative calculation in Table VII-25.

^q Some evidence has been found linking both PM and ozone exposures with premature mortality. The SAB has raised concerns that mortality-related benefits of air pollution reductions may be overstated if separate pollutant-specific estimates, some of which may have been obtained from models excluding the other pollutants, are aggregated. In addition, there may be important interactions between pollutants and their effect on mortality (EPA-SAB-Council-ADV-99-012, 1999).

Because of concern about overstating of benefits and because the evidence associating mortality with exposure to PM is currently stronger than for ozone, only the benefits related to the long-term exposure study

Health effects related to both PM and ozone include hospital admissions, asthma attacks, and minor restricted activity days.

For this analysis, we rely on C-R functions estimated in published epidemiological studies relating serious health effects to ambient air quality. The specific studies from which C-R functions are drawn are included in Table VII-14. A complete discussion of the C-R functions used for this analysis and information about each endpoint are contained in the benefits TSD for this RIA (Abt Associates, 2000).

While a broad range of serious health effects have been associated with exposure to elevated ozone and PM levels (as noted for example in Table VII-1 and described more fully in the ozone and PM Criteria Documents (US EPA, 1996a, 1996b), we include only a subset of health effects in this quantified benefit analysis. Health effects are excluded from this analysis for three reasons: (i) the possibility of double counting (such as hospital admissions for specific respiratory diseases); (ii) uncertainties in applying effect relationships based on clinical studies to the affected population; or (iii) a lack of an established C-R relationship.

When a single published study is selected as the basis of the C-R relationship between a pollutant and a given health effect, or “endpoint,” applying the C-R function is straightforward. This is the case for most of the health endpoints selected for inclusion in the benefits analysis. A single C-R function may be chosen over other potential functions because the underlying epidemiological study used superior methods, data or techniques, or because the C-R function is more generalized and comprehensive.

(ACS/Krewski, et al, 2000) of mortality are included in the total primary benefits estimate. The benefits associated with ozone reductions are presented as a sensitivity analysis in Appendix VII-A but are not included in the estimate of total benefits.

Table VII-14. Endpoints and Studies Included in the Primary Analysis

Endpoint	Pollutant	Study	Study Population
Premature Mortality			
Long-term exposure	PM _{2.5}	Krewski, et al. (2000) ^A	Adults, 30 and older
Chronic Illness			
Chronic Bronchitis (pooled estimate)	PM _{2.5}	Abbey, et al. (1995)	> 26 years
	PM ₁₀	Schwartz, et al. (1993)	> 29 years
Hospital Admissions			
All Respiratory	Ozone	Pooled estimate (8 studies)	All ages
COPD	PM	Samet, et al. (2000)	> 64 years
Pneumonia	PM	Samet, et al. (2000)	> 64 years
Asthma	PM	Sheppard, et al. (1999)	< 65 years
Total Cardiovascular	PM	Samet, et al. (2000)	> 64 years
Cardiac Dysrhythmias	Ozone	Burnett, et al. (1999)	All ages
Asthma-Related ER Visits	Ozone	Pooled estimate (3 studies)	All ages
Asthma-Related ER Visits	PM	Schwartz, et al. (1993)	All ages
Other Illness			
Asthma Attacks	PM, Ozone	Whittemore and Korn (1980)	Asthmatics, all ages
Acute Bronchitis	PM	Dockery et al. (1996)	Children, 8-12 years
Upper Respiratory Symptoms	PM	Pope et al. (1991)	Asthmatic children, 9-11
Lower Respiratory Symptoms	PM	Schwartz et al. (1994)	Children, 7-14 years
Work Loss Days	PM	Ostro (1987)	Adults, 18-65 years
Minor Restricted Activity Days (minus asthma attacks)	PM, Ozone	Ostro and Rothschild (1989)	Adults, 18-65 years

^A Estimate derived from Table 31, PM_{2.5}(DC), All Causes Model (Relative Risk = 1.12 for a 24.5 µg/m³ increase in mean PM_{2.5}).

When several estimated C-R relationships between a pollutant and a given health endpoint have been selected, they are combined or pooled to derive a single estimate of the relationship. The benefits TSD provides details of the procedures used to combine multiple C-R functions (Abt Associates, 2000). For example, pooled C-R functions are used to estimate incidences of chronic bronchitis related to PM exposure and to estimate hospital admissions for all respiratory causes and asthma-related emergency room visits related to ozone exposure.

Whether the C-R relationship between a pollutant and a given health endpoint is estimated by a single function from a single study or by a pooled function of C-R functions from several studies, we apply that same C-R relationship to all locations in the U.S. Although the C-R relationship may in fact vary somewhat from one location to another (for example, due to differences in population susceptibilities or differences in the composition of PM), location-

specific C-R functions are generally not available. A single function applied everywhere may result in overestimates of incidence changes in some locations and underestimates in other locations, but these location-specific biases will, to some extent, cancel each other out when the total incidence change is calculated. It is not possible to know the extent or direction of the bias in the total incidence change based on the general application of a single C-R function everywhere.

The appropriate economic value of a change in a health effect depends on whether the health effect is viewed *ex ante* (before the effect has occurred) or *ex post* (after the effect has occurred). Reductions in ambient concentrations of air pollution generally lower the risk of future adverse health effects by a fairly small amount for a large population. The appropriate economic measure is therefore *ex ante* WTP for changes in risk. However, epidemiological studies generally provide estimates of the relative risks of a particular health effect avoided due to a reduction in air pollution. A convenient way to use this data in a consistent framework is to convert probabilities to units of avoided statistical incidences. This measure is calculated by dividing individual WTP for a risk reduction by the related observed change in risk. For example, suppose a measure is able to reduce the risk of premature mortality from 2 in 10,000 to 1 in 10,000 (a reduction of 1 in 10,000). If individual WTP for this risk reduction is \$100, then the WTP for an avoided statistical premature mortality amounts to \$1 million ($\$100/0.0001$ change in risk). Using this approach, the size of the affected population is automatically taken into account by the number of incidences predicted by epidemiological studies applied to the relevant population. The same type of calculation can produce values for statistical incidences of other health endpoints.

For some health effects, such as hospital admissions, WTP estimates are generally not available. In these cases, we use the cost of treating or mitigating the effect as a primary estimate. For example, for the valuation of hospital admissions we use the avoided medical costs as an estimate of the value of avoiding the health effects causing the admission. These costs of illness (COI) estimates generally understate the true value of reductions in risk of a health effect. They tend to reflect the direct expenditures related to treatment but not the value of avoided pain and suffering from the health effect. Table VII-15 summarizes the value estimates per health effect that we used in this analysis. Note that the unit values for hospital admissions are the weighted averages of the ICD-9 code-specific values for the group of ICD-9 codes included in the hospital admission categories. Details of the derivation of values for hospital admissions can be found in the benefits TSD for this RIA (Abt Associates, 2000).

In the following sections, we describe individual health endpoints and the C-R functions we have selected to provide quantified estimates of the avoided health effects associated with the final HD Engine/Diesel Fuel rule. In addition, we discuss how these changes in health effects should be valued and indicate the value functions selected to provide monetized estimates of the value of changes in health effects.

Table VII-15. Unit Values Used for Economic Valuation of Health Endpoints

Health or Welfare Endpoint	Estimated Value Per Incidence (1999\$) Central Estimate	Derivation of Estimates
Premature Mortality	\$6 million per statistical life	Value is the mean of value-of-statistical-life estimates from 26 studies (5 contingent valuation and 21 labor market studies) reviewed for the Section 812 Costs and Benefits of the Clean Air Act, 1990-2010 (US EPA, 1999).
Chronic Bronchitis (CB)	\$331,000	Value is the mean of a generated distribution of WTP to avoid a case of pollution-related CB. WTP to avoid a case of pollution-related CB is derived by adjusting WTP (as described in Viscusi et al., 1991) to avoid a severe case of CB for the difference in severity and taking into account the elasticity of WTP with respect to severity of CB.
Hospital Admissions		
Chronic Obstructive Pulmonary Disease (COPD) (ICD codes 490-492, 494-496)	\$12,378	The COI estimates are based on ICD-9 code level information (e.g., average hospital care costs, average length of hospital stay, and weighted share of total COPD category illnesses) reported in Elixhauser (1993).
Pneumonia (ICD codes 480-487)	\$14,693	The COI estimates are based on ICD-9 code level information (e.g., average hospital care costs, average length of hospital stay, and weighted share of total pneumonia category illnesses) reported in Elixhauser (1993).
Asthma admissions	\$6,634	The COI estimates are based on ICD-9 code level information (e.g., average hospital care costs, average length of hospital stay, and weighted share of total asthma category illnesses) reported in Elixhauser (1993).
All Cardiovascular (ICD codes 390-429)	\$18,387	The COI estimates are based on ICD-9 code level information (e.g., average hospital care costs, average length of hospital stay, and weighted share of total cardiovascular illnesses) reported in Elixhauser (1993).
Emergency room visits for asthma	\$299	COI estimate based on data reported by Smith, et al. (1997).

Table VII-15. Unit Values Used for Economic Valuation of Health Endpoints

Health or Welfare Endpoint	Estimated Value Per Incidence (1999\$) Central Estimate	Derivation of Estimates
Respiratory Ailments Not Requiring Hospitalization		
Upper Respiratory Symptoms (URS)	\$24	Combinations of the 3 symptoms for which WTP estimates are available that closely match those listed by Pope, et al. result in 7 different “symptom clusters,” each describing a “type” of URS. A dollar value was derived for each type of URS, using mid-range estimates of WTP (IEc, 1994) to avoid each symptom in the cluster and assuming additivity of WTPs. The dollar value for URS is the average of the dollar values for the 7 different types of URS.
Lower Respiratory Symptoms (LRS)	\$15	Combinations of the 4 symptoms for which WTP estimates are available that closely match those listed by Schwartz, et al. result in 11 different “symptom clusters,” each describing a “type” of LRS. A dollar value was derived for each type of LRS, using mid-range estimates of WTP (IEc, 1994) to avoid each symptom in the cluster and assuming additivity of WTPs. The dollar value for LRS is the average of the dollar values for the 11 different types of LRS.
Acute Bronchitis	\$57	Average of low and high values recommended for use in Section 812 analysis (Neumann, et al. 1994)
Restricted Activity and Work Loss Days		
Work Loss Days (WLDs)	Variable	Regionally adjusted median weekly wage for 1990 divided by 5 (adjusted to 1999\$) (US Bureau of the Census, 1992).
Minor Restricted Activity Days (MRADs)	\$48	Median WTP estimate to avoid one MRAD from Tolley, et al. (1986) .

a. Premature Mortality: Quantification

Both acute and chronic exposures to ambient levels of air pollution have been associated with increased risk of premature mortality. Because of the extreme nature of this endpoint and the high monetary value associated with risks to life, reductions in the risk of premature mortality are the most important health endpoints quantified in this analysis. Although these endpoints account for over 90 percent of the total monetized benefits, considerable uncertainty exists, both among economists and policymakers, as to the appropriate way to value reductions in mortality risks. Because of these factors, we include a more detailed discussion for premature mortality than for other health effects.

Health researchers have consistently linked air pollution, especially PM, with increases in premature mortality. A substantial body of published scientific literature recognizes a correlation between elevated PM concentrations and increased mortality rates. Much of this literature is

summarized in the 1996 PM Criteria Document (US EPA, 1996a). There is much about this relationship that is still uncertain. As stated in preamble to the 1997 PM National Ambient Air Quality Standards (40 CFR 50, 1997), “the consistency of the results of the epidemiological studies from a large number of different locations and the coherent nature of the observed effects are suggestive of a likely causal role of ambient PM in contributing to the reported effects,” which include premature mortality. The National Academy of Sciences, in their report on research priorities for PM (NAS, 1998), indicates that “there is a great deal of uncertainty about the implications of the findings [of an association between PM and premature mortality] for risk management, due to the limited scientific information about the specific types of particles that might cause adverse health effects, the contributions of particles of outdoor origin to actual human exposures, the toxicological mechanisms by which the particles might cause adverse health effects, and other important questions.” EPA acknowledges these uncertainties; however, for this analysis, we assume a causal relationship between exposure to elevated PM and premature mortality, based on the consistent evidence of a correlation between PM and mortality reported in the scientific literature (US EPA, 1996a).

In addition, it is currently unknown whether there is a time lag (a delay between changes in PM exposures and changes in mortality rates) in the chronic PM/premature mortality relationship. The existence of such a lag is important for the valuation of premature mortality incidences because economic theory suggests that benefits occurring in the future should be discounted. Although there is no specific scientific evidence of the existence or structure of a PM effects lag, current scientific literature on adverse health effects, such as those associated with PM (e.g., smoking-related disease) and the difference in the effect size between chronic exposure studies and daily mortality studies suggest that all incidences of premature mortality reduction associated with a given incremental change in PM exposure probably would not occur in the same year as the exposure reduction. This same smoking-related literature implies that lags of up to a few years are plausible. Adopting the lag structure used in the Tier 2/Gasoline Sulfur RIA and endorsed by the SAB (EPA-SAB-COUNCIL-ADV-00-001, 1999), we assume a five-year lag structure, with 25 percent of premature deaths occurring in the first year, another 25 percent in the second year, and 16.7 percent in each of the remaining three years. To explore the uncertainty surrounding this lag structure, Appendix VII-A contains a sensitivity analysis showing how different lag structures affect the estimated value of reductions in premature mortality.

Two types of exposure studies (short-term and long-term exposure) have been used to estimate a PM/premature mortality relationship. Short-term exposure studies attempt to relate short-term (often day-to-day) changes in PM concentrations and changes in daily mortality rates up to several days after a period of elevated PM concentrations. Long-term exposure studies examine the potential relationship between longer-term (e.g., one or more years) exposure to PM and annual mortality rates. Researchers have found significant associations using both types of studies (US EPA, 1996a); however, for this analysis, we follow SAB advice (EPA-SAB-COUNCIL-ADV-99-005, 1999), and we rely exclusively on long-term exposure studies to quantify mortality effects.

Following advice from the SAB (EPA-SAB-COUNCIL-ADV-99-005, 1999), we prefer to use long-term exposure studies that employ a prospective cohort design over those that use an ecologic or population-level design. Prospective cohort studies follow individuals forward in time for a specified period, periodically evaluating each individual's exposure and health status. While the long-term exposure study design is preferred, they are expensive to conduct and consequently there are relatively few well designed long-term exposure studies. For PM, there have been only a few, and the SAB has explicitly recommended use of only one — the American Cancer Society (ACS) Study, as reported in Pope, et al. (1995) (EPA-SAB-COUNCIL-ADV-99-005, 1999). The data from this study were reanalyzed and we used a C-R function from the HEI reanalysis (ACS/Krewski et al., 2000).

The ACS/Pope, et al. study used a prospective cohort design to estimate the risk of premature mortality from long-term exposures to ambient PM concentrations. The ACS/Pope, et al. study is recommended in preference to other available long-term studies because it uses better statistical methods, has a much larger sample size and uses the longer exposure intervals, and more locations (50 cities) in the U.S. than other studies. Recently, the Health Effects Institute (HEI), a non-profit, independent research organization commissioned an extensive reanalysis of the data used in the ACS/Pope, et al. (1995) study.^f

The HEI reanalysis, as reported in Krewski, et al. (2000) and mentioned above, confirmed the general findings of the ACS/Pope, et al (1995) study. In addition, the reanalysis tested a number of alternative model specifications, some of which may be preferred to the original ACS/Pope, et al. (1995) specification. One important alternative specification examines the relationship between relative risk of premature mortality and mean PM_{2.5} levels rather than median levels used in the Pope, et al. (1995) analysis (Table 31, “PM_{2.5}(DC)” model). For policy analysis purposes, functions based on the mean air quality levels may be preferable to functions based on the median air quality levels because changes in the mean more accurately reflect changes in peak values than do changes in the median. Policies which affect peak PM days more than average PM days will result in a larger change in the mean than in the median. In these cases, all else being equal, C-R functions based on median PM_{2.5} will lead to lower estimates of avoided incidences of premature mortality than C-R functions based on mean PM_{2.5}. In addition to specifying a preference for the ACS study based on the larger set of cities examined, the SAB has also noted a preference for applying mean PM_{2.5} in premature mortality functions (US EPA-SAB, 1999). For these reasons, we have selected the C-R function based on the relative risk of 1.12 from the “PM2.5(DC), All Causes” model reported in Table 31 of the HEI report.^s

^fAdditional information on the Health Effects Institute and the reanalysis of the Harvard Six Cities and American Cancer Society Studies can be obtained at <http://www.healtheffects.org>.

^s Note that in several recent RIAs, we erroneously applied the ACS/Pope et al. C-R function to a baseline of non-accidental mortality. The correct baseline, matching the mortality measured in the ACS/Pope et al. and Krewski et al. studies is all-cause mortality. This correction results in a slight increase in the estimated mortality reductions resulting from a reduction in PM_{2.5}.

Although we use the Krewski, et al. (2000) mean-based (“PM_{2.5}(DC), All Causes”) model exclusively to derive our primary estimates of avoided premature mortality, we also examine the impacts of selecting alternative C-R functions for premature mortality. There are several candidates for alternative C-R functions, some from the Krewski, et al. study, and others from the original ACS study by Pope, et al. or from the “Harvard Six-City Study” by Dockery, et al. (1993).

Commentary by an independent review panel noted that “a major contribution of the [HEI] Reanalysis Project is the recognition that both pollutant variables and mortality appear to be spatially correlated in the ACS data set. If not identified and modeled correctly, spatial correlation could cause substantial errors in both the regression coefficients and their standard errors (HEI, 2000).” The HEI reanalysis provides results for several models which control for spatial correlations in the data. These models are based on the original ACS air quality dataset, which contained only median PM_{2.5} concentrations. Ideally, our primary C-R function for premature mortality would be both based on the mean and adjusted for regional variability. Unfortunately, Krewski, et al. do not provide such an estimate. As such, we have chosen to use the mean-based relative risk in our primary analysis and to use the median-based regionally adjusted relative risks to provide alternative estimates exploring the impact of adjustments for spatial correlations (see Table VII-16).

Krewski, et al. (2000) also reanalyzed the data from another prospective cohort study (the Harvard “Six Cities Study”) authored by Dockery, et al. (1993). The Dockery, et al. (1993) study used a smaller sample of individuals from fewer cities than the study by Pope, et al.; however, it features improved exposure estimates, a slightly broader study population (adults aged 25 and older), and a follow-up period nearly twice as long as that of Pope, et al. The SAB has noted that “the [Harvard Six Cities] study had better monitoring with less measurement error than did most other studies” (EPA-SAB-COUNCIL-ADV-99-012, 1999). The Dockery, et al. (1993) study finds a larger effect of PM on premature mortality relative to the Pope, et al. (1995) study. To provide a more complete picture of the range of possible premature mortality risks that may be associated with long-term exposures to fine particles, we also present alternative estimates based on the Krewski, et al. (2000) reanalysis of the Dockery, et al. (1993) data and the original study estimates. The HEI commentary notes that “the inherent limitations of using only six cities, understood by the original investigators, should be taken into account when interpreting the results of the Six Cities Study.” We emphasize, that based on our understanding of the relative merits of the two datasets, the Krewski, et al. (2000) ACS model based on mean PM_{2.5} levels in 63 cities is the most appropriate model for analyzing the premature mortality impacts of the HD Engine/Diesel Fuel rule. It is thus used for our primary estimate of this important health effect.

Table VII-16 summarizes the alternative C-R functions for PM-related premature mortality. Note that the right most column provides a standardized estimate of the incidences of premature mortality that would be reduced by a one microgram reduction in PM_{2.5} applied to a population of one million. Note that the relative magnitude of the values will not necessarily correlate with the estimates of avoided incidences that will result from application of the HD Engine/Diesel Fuel reductions in PM_{2.5} to 2030 national populations. This is because some of the functions are based on changes in mean PM_{2.5} concentrations while others are based on median

PM_{2.5} concentrations. Estimated reductions in premature mortality will depend on both the size of the C-R coefficient and the change in the relevant PM_{2.5} metric (mean or median).

Table VII-16. Alternative Concentration-Response Models Relating Premature Mortality and Chronic Exposure to Fine Particulates

Model Description (as listed in the study)	# of Cities	PM Metric	Reported Relative Risk ^A (95% Confidence Interval)	Avoided Incidences of Premature Mortality per Million Population for a 1 µg/m ³ Decrease in PM _{2.5} ^B
PM2.5(DC), All Causes Source: Table 31, Krewski, et al. (2000)	63	Mean	1.12 (1.06-1.19)	68
Fine Particles Alone, Random Effects, Regional Adjustment Source: Table 46, Krewski, et al. (2000)	50	Median	1.16 (0.99-1.37)	89
Fine Particles Alone, Random Effects, Independent Cities Source: Table 46, Krewski, et al. (2000)	50	Median	1.29 (1.12-1.48)	152
All Combined, All Cause, Fine Particles Source: Table 3, Pope, et al. (1995) ^C	50	Median	1.17 (1.09-1.26)	90
All Causes, Extended, Age Time Axis: Table 3, Krewski, et al. (2000)	6	Mean	1.27 (1.09-1.48)	173
All Subjects Source: Table 3, Dockery, et al. (1993)	6	Mean	1.26 (1.08-1.47)	153

^A Reported relative risks for the Pope, et al. (1995) and Dockery, et al. (1993) studies are comparisons of mortality rates between most polluted and least polluted cities. For the Pope et al. study the relative risk is based on a difference in median PM_{2.5} levels of 24.5 µg/m³. For the Dockery, et al. study, the relative risk is based on a difference of 18.6 µg/m³. The Krewski, et al. reanalysis of the Pope, et al. study reports all relative risks based on a 24.5 µg/m³ difference for comparability with the Pope, et al. (1995) results, rather than comparing the means or medians of the most polluted and least polluted studies. Likewise, the Krewski, et al. reanalysis of the Dockery, et al. Harvard Six Cities study reports all relative risks based on a 18.6 µg/m³ difference for comparability with the Dockery, et al. (1993) study.

^B Assumes national all-cause mortality rate of 0.0147 per person for adults aged 30 and older and 0.0131 per person for adults aged 25 and older. (US Centers for Disease Control. 2000 *National Vital Statistics Reports* 48(11): Table 8).

^C The Pope, et al. estimate of the relative risk of premature mortality from fine particle exposure is the basis for the estimates of premature mortality found in the final Tier 2/Gasoline Sulfur rule.

b. Premature Mortality: Valuation

We estimate the monetary benefit of reducing premature mortality risk using the “value of statistical lives saved” (VSL) approach, even though the actual valuation is of small changes in mortality risk experienced by a large number of people. The VSL approach applies information from several published value-of-life studies to determine a reasonable benefit of preventing premature mortality. The mean value of avoiding one statistical death is estimated to be \$6 million in 1999 dollars. This represents an intermediate value from a variety of estimates that appear in the economics literature, and it is a value EPA has frequently used in RIAs for other rules and in the Section 812 Reports to Congress.

This estimate is the mean of a distribution fitted to the estimates from 26 value-of-life studies identified in the Section 812 reports as “applicable to policy analysis.” The approach and set of selected studies mirrors that of Viscusi (1992) (with the addition of two studies), and uses the same criteria as Viscusi in his review of value-of-life studies. The \$6 million estimate is consistent with Viscusi’s conclusion (updated to 1999\$) that “most of the reasonable estimates of the value of life are clustered in the \$3.7 to \$8.6 million range.” Five of the 26 studies are contingent valuation (CV) studies, which directly solicit WTP information from subjects; the rest are wage-risk studies, which base WTP estimates on estimates of the additional compensation demanded in the labor market for riskier jobs. As indicated in the previous section on quantification of premature mortality benefits, we assume for this analysis that some of the incidences of premature mortality related to PM exposures occur in a distributed fashion over the five years following exposure. To take this into account in the valuation of reductions in premature mortality, we apply an annual three percent discount rate to the value of premature mortality occurring in future years.¹

The economics literature concerning the appropriate method for valuing reductions in premature mortality risk is still developing. The adoption of a value for the projected reduction in the risk of premature mortality is the subject of continuing discussion within the economic and public policy analysis community. Regardless of the theoretical economic considerations, EPA prefers not to draw distinctions in the monetary value assigned to the lives saved even if they differ in age, health status, socioeconomic status, gender or other characteristic of the adult population.

Following the advice of the EEAC of the SAB, EPA currently uses the VSL approach in calculating the primary estimate of mortality benefits, because we believe this calculation to provide the most reasonable single estimate of an individual’s willingness to trade off money for

¹ The choice of a discount rate, and its associated conceptual basis, is a topic of ongoing discussion within the federal government. EPA adopted a 3 percent discount rate for its primary analysis in this case to reflect reliance on a “social rate of time preference” discounting concept. We have also calculated benefits and costs using a 7 percent rate consistent with an “opportunity cost of capital” concept to reflect the time value of resources directed to meet regulatory requirements. In this case, the benefit and cost estimates were not significantly affected by the choice of discount rate. Further discussion of this topic appears in EPA’s *Guidelines for Preparing Economic Analyses* (in press).

reductions in mortality risk (EPA-SAB-EEAC-00-013). While there are several differences between the labor market studies EPA uses to derive a VSL estimate and the particulate matter air pollution context addressed here, those differences in the affected populations and the nature of the risks imply both upward and downward adjustments. Table VII-17 lists some of these differences and the expected effect on the VSL estimate for air pollution-related mortality. For example, adjusting for age differences may imply the need to adjust the \$6 million VSL downward, but the involuntary nature of air pollution-related risks and the lower level of risk-aversion of the manual laborers in the labor market studies may imply the need for upward adjustments. In the absence of a comprehensive and balanced set of adjustment factors, EPA believes it is reasonable to continue to use the \$6 million value while acknowledging the significant limitations and uncertainties in the available literature.

Some economists emphasize that the value of a statistical life is not a single number relevant for all situations. Indeed, the VSL estimate of \$6 million (1999 dollars) is itself the central tendency of a number of estimates of the VSL for some rather narrowly defined populations. When there are significant differences between the population affected by a particular health risk and the populations used in the labor market studies, as is the case here, some economists prefer to adjust the VSL estimate to reflect those differences. Some of the alternative approaches that have been proposed for valuing reductions in mortality risk are discussed in Figure VII-6.

There is general agreement that the value to an individual of a reduction in mortality risk can vary based on several factors, including the age of the individual, the type of risk, the level of control the individual has over the risk, the individual's attitudes towards risk, and the health status of the individual. While the empirical basis for adjusting the \$6 million VSL for many of these factors does not yet exist, a thorough discussion of these factors is contained in the benefits TSD for this RIA (Abt Associates, 2000). EPA recognizes the need for investigation by the scientific community to develop additional empirical support for adjustments to VSL for the factors mentioned above.

Table VII-17. Expected Impact on Estimated Benefits of Premature Mortality Reductions of Differences Between Factors Used in Developing Applied VSL and Theoretically Appropriate VSL

Attribute	Expected Direction of Bias
Age	Uncertain, perhaps overestimate
Attitudes toward risk	Underestimate
Income	Uncertain
Voluntary vs. Involuntary	Uncertain, perhaps underestimate
Catastrophic vs. Protracted Death	Uncertain, perhaps underestimate

Figure VII-6. Alternative Approaches for Assessing the Value of Reduced Mortality Risk

Stated preference studies – These studies use survey responses to estimate WTP to avoid risks. *Strengths:* flexible approach allowing for appropriate risk context, good data on WTP for individuals. *Weaknesses:* risk information may not be well-understood by respondents and questions may be unfamiliar.

Consumer market studies – These studies use consumer purchases and risk data (e.g., smoke detectors) to estimate WTP to avoid risks. *Strengths:* uses revealed preferences and is a flexible approach. *Weaknesses:* very difficult to estimate both risk and purchase variables.

Value of statistical life year (VSLY) – Provides an annual equivalent to value of statistical life estimates. *Strengths:* provides financially accurate adjustment for age at death. *Weaknesses:* adjustment may not reflect how individuals consider life-years; assumes equal value for all remaining life-years.

Quality adjusted life year – Applies quality of life adjustment to life-extension data, uses cost-effectiveness data to value. *Strengths:* widely used in public health literature to assess private medical interventions. *Weaknesses:* lack of data on health state indices and life quality adjustments that are applicable to an air pollution context. Similar to VSLY, adjustment may not reflect how individuals consider life-years, and typically assumes an equal value for all remaining life-years despite evidence to the contrary.

WTP for a change in survival curve – Reflects WTP for change in risk, potentially incorporates age-specific nature of risk reduction. *Strengths:* theoretically preferred approach that most accurately reflects risk reductions from air pollution control. *Weaknesses:* almost no empirical literature available; difficulty in obtaining reliable values.

WTP for a change in longevity – Uses stated preference approach to generate WTP for longevity or longer life expectancy. *Strengths:* life expectancy is a familiar term to most individuals. *Weaknesses:* does not incorporate age-specific risk information; problems in adapting to air pollution context.

Cost-effectiveness – Determines the implicit cost of saving a life or life-year. *Strengths:* widely used in public health contexts. *Weaknesses:* health context is for private goods, dollar values do not necessarily reflect individual preferences.

One important factor in Figure VII-6 for which the impact on total benefits can be illustrated is the difference in age distribution between the population affected by air pollution and the population for which most of the VSL estimates were developed. In the recent Tier 2/Gasoline Sulfur benefits analysis, we employed a value of statistical life years (VSLY) approach developed for the Section 812 studies in exploring the impact of age on VSL. Since the VSLY alternative calculation was introduced in the Section 812 studies, the SAB raised new and additional concerns about the merits of the VSLY approach. Specifically, they note in their recent report that “inferring the value of a statistical life year, however, requires assumptions about the discount rate and about the time path of expected utility of consumption” (EPA-SAB-EEAC-00-013). In considering the merits of age-based adjustments, the Committee also notes that “the theoretically appropriate method is to calculate WTP for individuals whose ages correspond to those of the affected population, and that it is preferable to base these calculations on empirical estimates of WTP by age.” Several studies conducted by Jones-Lee, et al. (1985, 1989, 1993) found a significant effect of age on the value of mortality risk reductions expressed

by citizens in the United Kingdom. Using the results of the Jones-Lee et al. analysis, U.S. EPA (2000b) calculated ratios of the value of life for different age groups to the mean value of life estimated by Jones-Lee, et al. (1989, 1993). The Jones-Lee-based analysis suggests a U-shaped relationship between age and VSL, peaking around age 40, and declining to between 60 and 90 percent of the mean VSL value for individuals over the age of 70, and declining further as individuals age. This finding has been supported by two recent analyses conducted by Krupnick, et al. (2000a, 2000b), which asked samples of Canadian and U.S. residents their values for reductions in mortality risk. We apply the ratios based on the Jones-Lee, et al. (1989, 1993) studies to the estimated premature mortalities within the appropriate age groups to provide an alternative age-adjusted estimate of the value of avoided premature mortalities. However, we have not attempted in this analysis to provide a consistent treatment of age-dependence between the underlying wage-risk studies and the present calculation. Therefore, the downward adjustment for age relative to our primary benefit estimate may be significantly overestimated, implying a significant underestimation of age-adjusted total benefits.

The SAB-EEAC advised in their recent report that the EPA “continue to use a wage-risk-based VSL as its primary estimate, including appropriate sensitivity analyses to reflect the uncertainty of these estimates,” and that “the only risk characteristic for which adjustments to the VSL can be made is the timing of the risk”(EPA-SAB-EEAC-00-013). In developing our primary estimate of the benefits of premature mortality reductions, we have discounted over the lag period between exposure and premature mortality. However, in accordance with the SAB advice, we use the VSL in our primary estimate and present the Jones-Lee calculations in the table of alternative calculations, Table VII-25.

c. Chronic Bronchitis: Quantification

Chronic bronchitis is characterized by mucus in the lungs and a persistent wet cough for at least three months a year for several years in a row. Chronic bronchitis affects an estimated five percent of the U.S. population (American Lung Association, 1999). There are a limited number of studies that have estimated the impact of air pollution on new incidences of chronic bronchitis. Schwartz (1993) and Abbey, et al.(1995) provide evidence that long-term PM exposure gives rise to the development of chronic bronchitis in the U.S. Following the same approaches, the Section 812 Prospective Report (US EPA, 1999a), our analysis pools the estimates from these studies to develop a C-R function linking PM to chronic bronchitis. The Schwartz (1993) study examined the relationship between exposure to PM₁₀ and prevalence of chronic bronchitis. The Abbey, et al. (1995) study examined the relationship between PM_{2.5} and new incidences of chronic bronchitis. Both studies have strengths and weaknesses which suggest that pooling the effect estimates from each study may provide a better estimate of the expected change in incidences of chronic bronchitis than using either study alone. However, the HD Engine/Diesel Fuel rule is expected to result in reductions in both the fine and coarse fractions of PM₁₀. As such, reliance on the Abbey, et al. (1995) estimate will result in an underestimate of the change in chronic bronchitis incidences if both the fine and coarse fractions of PM₁₀ are associated with chronic bronchitis. To address this problem, we apply the C-R functions from both Schwartz (1993) and Abbey, et al. (1995) to generate the changes in chronic bronchitis incidences associated with the change in PM_{2.5} and then pool the incidence estimates to obtain a

primary estimate of avoided $PM_{2.5}$ related chronic bronchitis incidences. We then apply the Schwartz (1993) C-R function to the change in coarse PM ($PM_{2.5-10}$) to obtain a primary estimate of avoided incidences of chronic bronchitis due to the change in coarse fraction PM. The primary estimate of total avoided incidences is then the sum of the avoided incidences from changes in $PM_{2.5}$ and $PM_{2.5-10}$.^u

It should be noted that Schwartz used data on the *prevalence* of chronic bronchitis, not its *incidence*. Following the Section 812 Prospective Report, we assume that it is appropriate to estimate the percentage change in the prevalence rate for chronic bronchitis using the estimated coefficient from Schwartz's study in a C-R function, and then to assume this percentage change applies to a baseline incidence rate obtained from another source. For example, if the prevalence declines by 25 percent with a drop in PM, then baseline incidence drops by 25 percent with the same drop in PM.

d. Chronic Bronchitis: Valuation

The best available estimate of WTP to avoid a case of chronic bronchitis (CB) comes from Viscusi, et al. (1991).^v The Viscusi, et al. study, however, describes a severe case of CB to the survey respondents. We therefore employ an estimate of WTP to avoid a pollution-related case of CB, based on adjusting the Viscusi, et al. (1991) estimate of the WTP to avoid a severe case. This is done to account for the likelihood that an average case of pollution-related CB is not as severe. The adjustment is made by applying the elasticity of WTP with respect to severity reported in the Krupnick and Cropper (1992) study. Details of this adjustment procedure are provided in the benefits TSD for this RIA (Abt Associates, 2000).

We use the mean of a distribution of WTP estimates as the central tendency estimate of WTP to avoid a pollution-related case of CB in this analysis. The distribution incorporates uncertainty from three sources: (1) the WTP to avoid a case of severe CB, as described by Viscusi, et al.; (2) the severity level of an average pollution-related case of CB (relative to that of the case described by Viscusi, et al.); and (3) the elasticity of WTP with respect to severity of the illness. Based on assumptions about the distributions of each of these three uncertain components, we derive a distribution of WTP to avoid a pollution-related case of CB by statistical uncertainty analysis techniques. The expected value (i.e., mean) of this distribution,

^u This assumption implies that the observed relationship between chronic bronchitis and PM_{10} in the Schwartz (1993) study is equally attributable to the fine and coarse fractions of PM_{10} . If the relationship is due primarily to the fine fraction, then the estimate of avoided incidences associated with coarse fraction PM changes will be overstated. However, if this is the case then the estimate of avoided incidences associated with fine fraction will be somewhat understated. The net effect on avoided incidences of chronic bronchitis is ambiguous.

^vThe Viscusi, et al. (1991) study was an experimental study intended to examine new methodologies for eliciting values for morbidity endpoints. Although these studies were not specifically designed for policy analysis, the SAB (EPA-SAB-COUNCIL-ADV-00-002, 1999) has indicated that the severity-adjusted values from this study provide reasonable estimates of the WTP for avoidance of chronic bronchitis. As with other contingent valuation studies, the reliability of the WTP estimates depends on the methods used to obtain the WTP values.

which is about \$331,000 (1999\$), is taken as the central tendency estimate of WTP to avoid a PM-related case of CB.

e. **Hospital and Emergency Room Admissions: Quantification**

There is a wealth of epidemiological information on the relationship between air pollution and hospital admissions for various respiratory and cardiovascular diseases; in addition, some studies have examined the relationship between air pollution and emergency room (ER) visits. Because most ER visits do not result in an admission to the hospital (the majority of people going to the ER are treated and return home) we treat hospital admissions and ER visits separately, taking account of the fraction of ER visits that are admitted to the hospital.

Hospital admissions require the patient to be examined by a physician, and on average may represent more serious incidents than ER visits. The two main groups of hospital admissions estimated in this analysis are respiratory admissions and cardiovascular admissions. There is not much evidence linking ozone or PM with other types of hospital admissions. The only type of ER visits that have been linked to ozone and PM in the U.S. are asthma-related visits.

i. *PM-related Hospital Admissions*

To estimate avoided incidences of hospital admissions associated with PM, we use a study by Samet, et al. (2000) which examined the relationship between PM_{10} and admissions for pneumonia, chronic obstructive pulmonary disease (COPD), and cardiovascular disease in fourteen U.S. cities. In previous analyses, we have pooled estimates from a number of studies in different cities. However, Samet, et al. (2000) represents a comprehensive analysis of the relationship between hospital admissions and air pollution conducted under the auspices of the Health Effects Institute as part of the National Morbidity, Mortality, and Air Pollution study. This extensive analysis by the HEI was intended to provide a consistent, comparable set of effects estimates over a wide range of cities. As such, the pooled estimates of relative risk for pneumonia, COPD, and cardiovascular disease provided by the study (Table 14, “Unconstrained distributed lag, Random effects estimate”), which covers most of the studies included individually in previous benefits analyses, represents the most up-to-date estimate of the relationship between PM air pollution and hospital admissions. One study (Moolgavkar, 1997) found a much lower effect of PM on hospital admissions for pneumonia and COPD. The effect of using Moolgavkar (1997) instead of Samet, et al. (2000) is presented as an alternative calculation in Table VII-25.

The Samet, et al. (2000) HEI analysis estimated separate C-R functions for pneumonia and COPD hospital admissions for people 65 years and older. In addition, Sheppard, et al. (1999) estimated a C-R function for asthma hospital admissions for people under age 65. These three estimates can be combined to calculate total avoided incidences of PM-related respiratory-related hospital admissions.

To estimate the effects of PM air pollution reductions on asthma-related ER visits, we use the C-R function based on a study of Seattle residents by Schwartz, et al. (1993). Because we are

estimating ER visits as well as hospital admissions for asthma, we must avoid counting twice the ER visits for asthma that are subsequently admitted to the hospital. To avoid double-counting, the baseline incidence rate for ER visits is adjusted by subtracting the percentage of patients that are admitted into the hospital. The reported incidence rates suggest that ER visits for asthma occur 2.7 times as frequently as hospital admissions for asthma. The baseline incidence of asthma ER visits is therefore taken to be 2.7 times the baseline incidence of hospital admissions for asthma. To avoid double-counting, however, only 63 percent of the resulting change in asthma ER visits associated with a given change in pollutant concentrations is counted in the ER visit incidence change.

ii. Ozone-related Hospital Admissions

To estimate avoided incidences of hospital admissions associated with ozone, we use a number of studies examining hospital admissions for a range of respiratory illnesses and one study examining hospital admissions for cardiac dysrhythmias. Hospital admissions for respiratory diseases studied include admissions for pneumonia, COPD, asthma, and a number of other respiratory illnesses. Hospital admissions for cardiac dysrhythmias are estimated using a C-R function derived from Burnett, et al. (1999).

f. Hospital Admissions: Valuation

An individual's WTP to avoid a hospital admission will include, at a minimum, the amount of money he or she pays for medical expenses (i.e., payment towards the hospital charge and the associated physician charge) and the loss in earnings. In addition, an individual is likely to be willing to pay some amount to avoid the pain and suffering associated with the illness itself. Even if they incurred no medical expenses and no loss in earnings, most individuals would still be willing to pay something to avoid the illness.

In the absence of estimates of WTP to avoid hospital admissions for specific illnesses, estimates of total cost-of-illness (COI) are typically used although they underestimate the benefits. These estimates are biased downward because they do not include the value of avoiding the illness itself. Some analyses adjust COI estimates upward by multiplying by an estimate of the ratio of WTP to COI, to better approximate total WTP. Other analyses have avoided making this adjustment because of the possibility of over adjusting -- that is, possibly replacing a known downward bias with an upward bias. Consistent with the advice offered by the SAB, the COI values used in this benefits analysis will not be adjusted (EPA-SAB-COUNCIL-ADV-98-003, 1998).

For the valuation of avoided respiratory and cardiovascular hospital admissions, the current literature provides well-developed and detailed cost estimates of hospitalization by health effect or illness. Using illness-specific estimates of avoided medical costs and avoided costs of lost work-time that Elixhauser (1993) developed, we construct COI estimates specific to the suite of health effects defined by each C-R function. Using the methods developed for the Section 812 reports, ICD-code-specific COI estimates were generated based on estimated hospital charges and the estimated opportunity cost of time spent in the hospital (estimated as the value of the lost

daily wage, regardless of whether or not the individual is in the workforce). The value of an avoided asthma-related ER visit is based on data reported in Smith, et al. (1997). The average cost per ER visit reported in this study (1999\$) is \$298.62.

g. Asthma Attacks: Quantification

Asthma is the most prevalent chronic disease among children in the U.S., affecting over seven percent of children under 18 years old (US CDC, 1998). Among adults, it currently affects over six percent of the U.S. population (US CDC, 1998). Asthma attacks are a serious health effect for people with asthma. During an attack, muscles around the airways constrict, the airways become inflamed, and less air passes in and out of the lungs. The attack is also called an episode or exacerbation and can include coughing, chest tightness, wheezing, and difficulty breathing (Jack, Boss, and Millington, 2000). The literature supports a direct relationship between air pollution and increased incidence and severity of asthma-related respiratory symptoms. Studies have documented this relationship for both PM (Yu, et al., 2000; McConnell et al., 1999; Delfino et al., 1998; Delfino et al., 1997; US EPA, 1996a; Ostro et al., 1995; Whittemore and Korn, 1980) and ozone (Delfino et al., 1998; Thurston et al., 1997; US EPA, 1996b; Delfino et al., 1996; Ostro et al., 1995; US EPA, 1986; Whittemore and Korn, 1980).

There are a number of these studies showing a relationship between PM and/or ozone levels and asthma-related respiratory symptoms such as wheezing, coughing, acute bronchitis and shortness of breath. However, only one study (Whittemore and Korn, 1980) estimated the relationship between asthma attacks and photochemical air pollutant concentrations. The likely reason for the emphasis of most studies on particular asthma symptoms is the subjective definition of an asthma attack and the subsequent lack of specificity in measuring an asthma attack occurrence. In this analysis, the endpoint “asthma attack” is a better match for the economic valuation studies and avoids potential overprediction (as one attack may involve some combination of symptoms). Accordingly, an asthma attack is an endpoint that summarizes the collection of symptoms, so potential double-counting may occur if individual asthma symptoms estimated from other studies are summed. An asthma attack, as measured by Whittemore and Korn (1980), is based on subjective reporting by study participants and likely consisting of one or more of the respiratory symptoms listed above occurring at varying levels of severity. For example, a subject reporting an asthma attack in the Whittemore and Korn (1980) study may have shortness of breath and wheezing. This is accounted for as one attack, while using individual symptom studies would record this as two separate symptom occurrences. Conversely, a participant may experience symptoms but not consider the symptoms to be “an attack.” Thus, the use of “asthma attacks” as an indicator may understate symptoms.

In addition, a limited number of economic studies have been conducted on the value of reduced asthma symptoms. One valuation study by Rowe and Chestnut (1986) calculated the value of reduction in “bad asthma days,” which we interpret as equivalent to a day with an asthma attack. By using the Whittemore and Korn (1980) asthma attack C-R function in combination with the Rowe and Chestnut (1986) valuation study, we are able to provide a quantified and monetized estimate of asthma-related symptoms that is representative of the full spectrum of impacts of air pollution reductions on asthma sufferers.

Although the Whittemore and Korn (1980) study had a number of methodological flaws, including omission of some potentially confounding variables and use of proxies for ozone and PM^w, we believe that the more recent literature supports the general magnitude of the relationship. As such, we use Whittemore and Korn in our primary analysis to estimate the effects of air pollution on asthma symptoms, recognizing that the Whittemore and Korn based estimate represents symptoms examined in other studies, though perhaps undercounting the frequency of symptom occurrence. Other analyses of the impacts of air pollution reductions on asthma symptoms have used collections of asthma symptom studies (Kunzli et al., 2000). However, we believe it is more illustrative to provide a single endpoint that represents a combination of symptoms. The Whittemore and Korn study was also previously used to estimate asthma attacks in the Section 812 analysis (although it was not included in the primary estimate of total benefits), which was reviewed and accepted by the EPA SAB. Table VII-18 provides a summary of the more recent studies of air pollution and respiratory symptoms in asthmatics. Also, several asthma-related endpoints are provided as supplementary calculations in Appendix VII-A to this chapter.

Note that the estimated number of avoided asthma attacks is the total change over the full population of asthmatics, potentially including multiple avoided attacks for a single individual. Also, because our estimate of asthma attacks is based on both the incidence of asthma attacks and the prevalence of asthma in the population, to the extent that asthma incidence rates are increasing (or decreasing), the number of asthma attacks avoided will also be increasing (or decreasing). The prevalence of asthma, especially among children, has been increasing over the past two decades (Pew Environmental Health Commission, 2000), suggesting that if current trends continue, the impact on asthma symptoms of reductions in air pollution will be greater than we estimated in this analysis.

h. Asthma Attacks: Valuation

In the primary analysis, we do not present a monetized value. As an alternative, asthma attacks are valued at \$41 per incidence (1999\$), based on the mean of average WTP estimates for the four severity definitions of a “bad asthma day,” described in Rowe and Chestnut (1986). This study surveyed asthmatics to estimate WTP for avoidance of a “bad asthma day,” as defined by the subjects. For purposes of valuation, an asthma attack is assumed to be equivalent to a day in which asthma is moderate or worse as reported in the Rowe and Chestnut (1986) study. To the extent that an asthma attack differs from a “bad asthma day” as defined by Rowe and Chestnut (1986), the value of an asthma attack may be over or underestimated. Recent evidence from the United Kingdom (Hoskins et al., 2000) suggests that our value for avoided asthma attacks may understate true benefits by a significant amount. Hoskins et al. used a very specific definition of an asthma attack that is likely to be more severe than at least some of the asthma attacks reported by subjects in the Whittemore and Korn (1980) study. Using this definition, however, they found that asthmatics who suffered at least one asthma attack in a year had increased asthma-related costs of £273, or around \$450US (1999\$).

^wWhittemore and Korn used oxidants instead of ozone and TSP instead of PM₁₀.

Table VII-18. Recent Studies on the Effects of Air Pollution on Asthma Symptoms

Study	Location/ Date	Asthmatic Study Population ^A	Symptoms ^B	Pollutants	Main Findings for Ozone and PM Exposures ^C
McConnell, et al. (1999)	Southern CA, 1993	493 asthmatic children, ages 9-15	Bronchitis, Phlegm, Cough	PM ₁₀ , PM _{2.5} , NO ₂ , Ozone, Acid vapor	Significant effects of PM ₁₀ on bronchitis (OR=1.4, 95% CI =1.1, 1.4) and phlegm (OR=2.1, 95% CI=1.4, 3.3). Significant effect of PM _{2.5} on phlegm (OR=2.6, 95% CI=1.2, 5.4)
Delfino, et al. (1997)	Southern CA, 1994	22 asthmatics, ages 9-46	Symptom severity, PEFR, inhaler use	pollen, fungi, Ozone, PM ₁₀	Significant effect of PM ₁₀ on inhaler use (0.15 inhaler puffs/10 µg/m ³ , p<0.02)
Ostro, et al. (1995)	Los Angeles, 1992	83 African-American asthmatic children, ages 7-12	Shortness of breath	Ozone, PM ₁₀ , SO ₂ , NO ₂ , pollen, fungi	Significant effect of PM ₁₀ on shortness of breath (OR=1.6, 95% CI=1.1 ,2.4). Significant effect of ozone on shortness of breath (OR=1.4, 95% CI=1.0, 1.8)
Thurston, et al. (1997)	CT, 1991-1993	166 asthmatic children, ages 7-13	Chest symptoms, PEFR, inhaler use	Ozone, SO ₄ , Hydrogen ion	Significant effect ^D of ozone on chest symptoms (OR=1.4) and inhaler use (OR=1.4)
Delfino, et al. (1998)	Southern CA, 1995	25 asthmatic children, ages 9-17	Asthma symptom score	PM ₁₀ , ozone, fungi	Significant effect of 24-hr mean PM ₁₀ on asthma symptoms (OR=1.7, 95% CI=1.0, 2.7)
Delfino, et al. (1996)	San Diego, CA, 1993	12 asthmatic children, ages 9-16	Asthma symptom score, inhaler use	Ozone, PM _{2.5} , fungi	Significant effect of ozone on inhaler use (1.1 puffs/100 ppb, p<0.03) and symptom scores

^A Study population is not the only measure of the power of a statistical analysis. For some studies, such as the Delfino, et al. (1996) analysis, the relatively small number of subjects were followed for a period of time. Thus, the number of person-days in these studies is a better indicator of statistical power than the number of study subjects.

^B PEFR is peak expiratory flow rate, a measure of lung function.

^C OR is the odds ratios.

^D No 95% confidence interval was reported for the odds ratios in the Thurston, et al. (1997) study.

i. Other Health Effects: Quantification

As indicated in Table VII-1, in addition to mortality, chronic illness, and hospital admissions, there are a number of acute health effects not requiring hospitalization that are

associated with exposure to ambient levels of ozone and PM. The sources for the C-R functions used to quantify these effects are described below.

Around five percent of U.S. children between ages five and seventeen experience episodes of acute bronchitis annually (Adams, et al, 1995). Acute bronchitis is characterized by coughing, chest discomfort, and extreme tiredness. Incidences of acute bronchitis in children between the ages of five and seventeen are estimated using a C-R function developed from Dockery, et al. (1996).

Incidences of lower respiratory symptoms (i.e., wheezing, deep cough) in children aged seven to fourteen are estimated using a C-R function developed from Schwartz, et al. (1994).

Because asthmatics have greater sensitivity to stimuli (including air pollution), children with asthma can be more susceptible to a variety of upper respiratory symptoms (i.e., runny or stuffy nose; wet cough; and burning, aching, or red eyes). Research on the effects of air pollution on upper respiratory symptoms have thus focused on effects in asthmatics. Incidences of upper respiratory symptoms in asthmatic children aged nine to eleven are estimated using a C-R function developed from Pope, et al. (1991).

Health effects from air pollution can also result in missed days of work (either from personal symptoms or from caring for a sick family member). Work loss days are estimated using a C-R function developed from Ostro (1987).

The endpoint minor restricted activity days (MRAD) is estimated using a C-R function derived from Ostro and Rothschild (1989). Because MRADs are characterized by many of the same symptoms as those which define an asthma attack and the study population in Ostro and Rothschild did not exclude asthmatics, we reduce the estimated number of avoided MRAD incidences by the estimated number of avoided asthma attacks to prevent double-counting of asthma attacks. This simple subtraction may result in an underestimate of non-asthma attack related MRADs, since asthma attacks are estimated for asthmatics of all ages and MRADs are estimated only for ages 18 to 65. However, without further information on the percent of MRADs that are related to asthma attacks, we have chosen to provide a conservative estimate of MRAD benefits.

In addition to the health effects discussed above, human exposure to PM and ozone is believed to be linked to health effects such as ozone-related premature mortality (Ito and Thurston, 1996; Samet, et al. 1997), PM-related infant mortality (Woodruff, et al., 1997), cancer (US EPA, 1996b), increased emergency room visits for non-asthma respiratory causes (US EPA, 1996a; 1996b), impaired airway responsiveness (US EPA, 1996a), increased susceptibility to respiratory infection (US EPA, 1996a), acute inflammation and respiratory cell damage (US EPA, 1996a), premature aging of the lungs and chronic respiratory damage (US EPA, 1996a; 1996b). An improvement in ambient PM and ozone air quality may reduce the number of incidences within each effect category that the U.S. population would experience. Although these health effects are believed to be PM or ozone-induced, C-R data are not available for

quantifying the benefits associated with reducing these effects. The inability to quantify these effects lends a downward bias to the monetized benefits presented in this analysis.

Another category of potential effects that may change in response to ozone reduction strategies results from the shielding provided by ozone against the harmful effects of ultraviolet radiation (UV-B) derived from the sun. The great majority of this shielding results from naturally occurring ozone in the stratosphere, but the 10 percent of total “column” ozone present in the troposphere also contributes (NAS, 1991). A variable portion of this tropospheric fraction of UV-B shielding is derived from ground level or “smog” ozone related to anthropogenic air pollution. Therefore, strategies that reduce ground level ozone will, in some small measure, increase exposure to UV-B from the sun.

While it is possible to provide quantitative estimates of benefits associated with globally based strategies to restore the far larger and more spatially uniform stratospheric ozone layer, the changes in UV-B exposures associated with ground level ozone reduction strategies are much more complicated and uncertain. Smog ozone strategies, such as mobile source controls, are focused on decreasing peak ground level ozone concentrations, and it is reasonable to conclude that they produce a far more complex and heterogeneous spatial and temporal pattern of ozone concentration and UV-B exposure changes than do stratospheric ozone protection programs. In addition, the changes in long-term total column ozone concentrations are far smaller from ground-level programs. To properly estimate the change in exposure and impacts, it would be necessary to match the spatial and temporal distribution of the changes in ground-level ozone to the spatial and temporal distribution of exposure to ground level ozone and sunlight. More importantly, it is long-term exposure to UV-B that is associated with effects. Intermittent, short-term, and relatively small changes in ground-level ozone and UV-B are not likely to measurably change long-term risks of these adverse effects.

For all of these reasons, we were unable to provide reliable estimates of the changes in UV-B shielding associated with ground-level ozone changes. This inability lends an upward bias to the net monetized benefits presented in this analysis. It is likely that the adverse health effects associated with increases in UV-B exposure from decreased tropospheric ozone will, however, be relatively small because 1) the expected long-term ozone change resulting from this rule is small relative to total anthropogenic tropospheric ozone, which in turn is small in comparison to total column natural stratospheric and tropospheric ozone; 2) air quality management strategies are focused on decreasing peak ozone concentrations and thus may change exposures over limited areas for limited times; 3) people often receive peak exposures to UV-B in coastal areas where sea or lake breezes reduce ground level pollution concentrations regardless of strategy; and 4) ozone concentration changes are greatest in urban areas and areas immediately downwind of urban areas. In these areas, people are more likely to spend most of their time indoors or in the shade of buildings, trees or vehicles.

j. Other Health Effects: Valuation

The valuation of a specific short-term morbidity endpoint is generally estimated by representing the illness as a cluster of acute symptoms. For each symptom, the WTP is

calculated. These values, in turn, are aggregated to arrive at the WTP to avoid a specific short term condition. For example, the endpoint lower respiratory symptoms (LRS) is represented by two or more of the following symptoms: runny or stuffy nose; coughing; and eye irritation. The WTP to avoid one day of LRS is the sum of values associated with these symptoms. The primary advantage of this approach is that it provides some flexibility in constructing estimates to represent a variety of health effects.

Valuation estimates for individual minor health effects are listed in Table VII-16. Derivation of the individual valuation estimates is provided in the benefits TSD for this RIA. Mean estimates range from \$15 for an avoided day of lower respiratory symptoms to \$57 for an avoided incidence of acute bronchitis. The value of work loss days varies depending on the location of an affected population. Using the median daily wage, the representative value of a work loss day is \$106 (1999\$). However, depending on where an affected individual lives, the value of work loss day may be higher or lower than \$106.

k. Lost Worker Productivity: Quantification and Valuation

While not technically a health effect, lost worker productivity related to pollution exposure is presumably linked to reductions in the physical capabilities of workers in outdoor jobs. The value of lost worker productivity due to ozone exposure is directly estimated based on a study of California citrus workers (Crocker and Horst, 1981; US EPA, 1994). The study measured productivity impacts as the change in income associated with a change in ozone exposure, given as the elasticity of income with respect to ozone concentration (or the percentage change in income for a one percent change in ambient ozone concentration). The reported elasticity translates a ten percent reduction in ozone to a 1.4 percent increase in income.

l. Estimated Reductions in Incidences of Health Endpoints and Associated Monetary Values

Applying the C-R and valuation functions described above to the estimated changes in ozone and PM yields estimates of the number of avoided incidences (i.e. premature mortalities, cases, admissions, etc.) and the associated monetary values for those avoided incidences. These estimates are presented in Table VII-19. All of the monetary benefits are in constant 1999 dollars.

Not all known PM- and ozone-related health effects could be quantified or monetized. These unmonetized benefits are indicated by place holders, labeled B_1 and B_2 . In addition, unmonetized benefits associated with CO and NMHC reductions are indicated by the placeholders B_3 and B_4 . Unquantified physical effects are indicated by U_1 through U_4 . The estimate of total monetized health benefits is thus equal to the subset of monetized PM- and ozone-related health benefits plus B_H , the sum of the unmonetized health benefits.

An important factor to consider when interpreting the ozone-related benefits in Table VII-19 is the omission of ozone-related benefits in the Western U.S.^x Over 22 percent of national NO_x emission reductions occur in the Western U.S., with over 10 percent of total NO_x emissions occurring in California alone. This suggests that ozone benefits in the West may be substantial, and that our estimate of Eastern ozone benefits may significantly underestimate national ozone-related benefits of the HD Engine/Diesel Fuel NO_x reductions.

The largest monetized health benefit is associated with reductions in the risk of premature mortality, which accounts for over \$60 billion, which is over 90 percent of total monetized health benefits. The next largest benefit is for chronic bronchitis reductions, although this value is more than an order of magnitude lower than for premature mortality. Minor restricted activity days, work loss days, and worker productivity account for the majority of the remaining benefits. The remaining categories account for less than \$10 million each, however, they represent a large number of avoided incidences affecting many individuals. Alternative calculations for premature mortality incidences and valuation are presented in Tables VII-24 and VII-25, respectively. An alternative calculation is also provided in Table VII-25 for chronic bronchitis incidences and for chronic asthma incidences.

^x We define the Western U.S. as west of 100 degrees longitude.

Table VII-19. Primary Estimate of Annual Health Benefits Associated With Air Quality Changes Resulting from the HD Engine/Diesel Fuel Rule in 2030

Endpoint	Avoided Incidence ^A (cases/year)	Monetary Benefits ^B (millions 1999\$, not adjusted for growth in real income)	Monetary Benefits ^B (millions 1999\$, adjusted for growth in real income)
<i>PM-related Endpoints^C</i>			
Premature mortality ^D (adults, 30 and over)	8,300	\$48,250	\$62,580
Chronic bronchitis (adults, 26 and over)	5,500	\$1,810	\$2,430
Hospital Admissions – Pneumonia (adults, over 64)	1,100	\$20	\$20
Hospital Admissions – COPD (adults, 64 and over)	900	\$10	\$10
Hospital Admissions – Asthma (65 and younger)	900	\$10	\$10
Hospital Admissions – Cardiovascular (adults, over 64)	2,700	\$50	\$50
Emergency Room Visits for Asthma (65 and younger)	2,100	<\$5	<\$5
Asthma Attacks (asthmatics, all ages) ^E	175,900	B _a	B _a
Acute bronchitis (children, 8-12)	17,600	<\$5	<\$5
Lower respiratory symptoms (children, 7-14)	192,900	<\$5	<\$5
Upper respiratory symptoms (asthmatic children, 9-11)	193,400	\$10	\$10
Work loss days (adults, 18-65)	1,539,400	\$160	\$160
Minor restricted activity days (adults, age 18-65)	7,990,400	\$390	\$430
Other PM-related health effects ^E	U ₁	B ₁	B ₁
<i>Ozone-related Endpoints (Eastern U.S. only)^F</i>			
Hospital Admissions – Respiratory Causes (all ages)	1,200	\$20	\$20
Hospital Admissions – Cardiac Dysrhythmias (all ages)	300	<\$5	<\$5
Emergency Room Visits for Asthma (all ages)	300	<\$1	<\$1
Asthma Attacks (asthmatics, all ages) ^E	185,500	B _a	B _a
Minor restricted activity days (adults, age 18-65)	1,848,100	\$100	\$100
Decreased worker productivity (adult working population)	—	\$140	\$140
Other ozone-related health effects ^E	U ₂	B ₂	B ₂
CO and NMHC-related health effects ^E	U ₃ +U ₄	B ₃ + B ₄	B ₃ +B ₄
<i>Monetized Total Health-related Benefits^G</i>	—	\$50,980+B _H	\$65,970+B _H

^A Incidences are rounded to the nearest 100.

^B Dollar values are rounded to the nearest 10 million.

^C PM-related benefits are based on the assumption that Eastern U.S. nitrate reductions are equal to one-fifth the nitrate reductions predicted by REMSAD (see Chapter II for a discussion of REMSAD and model performance).

^D Premature mortality associated with ozone is not separately included in this analysis (also note that the estimated value for PM-related premature mortality assumes the 5 year distributed lag structure described in Section D-3.

^E A detailed listing of unquantified PM, ozone, CO, and NMHC related health effects is provided in Table VII-1. For some endpoints such as asthma attacks, we are able to quantify the reduction in incidence, but we present the monetization as an alternative calculation.

^F Ozone-related benefits are only calculated for the Eastern U.S. due to unavailability of reliable modeled ozone concentrations in the Western U.S. See Section C-3 for a detailed discussion of the UAM-V ozone model and model performance issues.

^G B_H is equal to the sum of all unmonetized categories, i.e. B_a+B₁+B₂+B₃+B₄.

E. Assessment of Human Welfare Benefits

PM and ozone have numerous documented effects on environmental quality that affect human welfare. These welfare effects include direct damages to property, either through impacts on material structures or by soiling of surfaces, direct economic damages in the form of lost productivity of crops and trees, indirect damages through alteration of ecosystem functions, and indirect economic damages through the loss in value of recreational experiences or the existence value of important resources. EPA's Criteria Documents for PM and ozone list numerous physical and ecological effects known to be linked to ambient concentrations of these pollutants (US EPA, 1996a; 1996b). This section describes individual effects and how we quantify and monetize them. These effects include changes in commercial crop and forest yields, visibility, and nitrogen deposition to estuaries.

In section 1, we describe how we quantify and value changes in visibility, both in federal Class I areas (national parks and wilderness areas) and in the areas where people live and work. In section 2, we describe how we value the benefits of increased agricultural and commercial forest yields resulting from decreased levels of ambient ozone. In section 3, we describe the damage to materials caused by particulate matter. In section 4, we discuss the effects of nitrogen deposition on ecosystems (especially estuarine ecosystems) and describe how we quantify changes in nitrogen loadings. Finally, in section 5, we summarize the monetized estimates for welfare effects. A more detailed description of these analyses can be found in the benefits TSD for this RIA (Abt Associates, 2000).

1. Visibility Benefits

Changes in the level of ambient particulate matter caused by the final HD Engine/Diesel Fuel rule will change the level of visibility in much of the U.S. Visibility directly affects people's enjoyment of a variety of daily activities. Individuals value visibility both in the places they live and work, in the places they travel to for recreational purposes, and at sites of unique public value, such as the Grand Canyon. This section discusses the measurement of the economic benefits of visibility.

It is difficult to quantitatively define a visibility endpoint that can be used for valuation. Increases in PM concentrations cause increases in light extinction. Light extinction is a measure of how much the components of the atmosphere absorb light. More light absorption means that the clarity of visual images and visual range is reduced, *ceteris paribus*. Light absorption is a variable that can be accurately measured. Sisler (1996) created a unitless measure of visibility based directly on the degree of measured light absorption called the *deciview*. Deciviews are standardized for a reference distance in such a way that one deciview corresponds to a change of about 10 percent in available light. Sisler characterized a change in light extinction of one deciview as "a small but perceptible scenic change under many circumstances." Air quality

models were used to predict the change in visibility, measured in deciviews, of the areas affected by the final HD Engine/Diesel Fuel rule.^y

EPA considers benefits from two categories of visibility changes: residential visibility and recreational visibility. In both cases economic benefits are believed to consist of both use values and non-use values. Use values include the aesthetic benefits of better visibility, improved road and air safety, and enhanced recreation in activities like hunting and birdwatching. Non-use values are based on people's beliefs that the environment ought to exist free of human-induced haze. Non-use values may be a more important component of value for recreational areas, particularly national parks and monuments.

Residential visibility benefits are those that occur from visibility changes in urban, suburban, and rural areas, and also in recreational areas **not** listed as federal Class I areas.^z For the purposes of this analysis, recreational visibility improvements are defined as those that occur specifically in federal Class I areas. A key distinction between recreational and residential benefits is that only those people living in residential areas are assumed to receive benefits from residential visibility, while all households in the U.S. are assumed to derive some benefit from improvements in Class I areas. Values are assumed to be higher if the Class I area is located close to their home.^{aa}

Only two existing studies provide defensible monetary estimates of the value of visibility changes. One is a study on residential visibility conducted in 1990 (McClelland, et. al., 1993) and the other is a 1988 survey on recreational visibility value (Chestnut and Rowe, 1990a; 1990b). Both utilize the contingent valuation method. There has been a great deal of controversy and significant development of both theoretical and empirical knowledge about how to conduct CV surveys in the past decade. In EPA's judgment, the Chestnut and Rowe study contains many of the elements of a valid CV study and is sufficiently reliable to serve as the basis for monetary estimates of the benefits of visibility changes in recreational areas.^{bb} This study serves as an

^y A change of less than 10 percent in the light extinction budget represents a measurable improvement in visibility, but may not be perceptible to the eye in many cases. Some of the average regional changes in visibility are less than one deciview (i.e. less than 10 percent of the light extinction budget), and thus less than perceptible. However, this does not mean that these changes are not real or significant. Our assumption is then that individuals can place values on changes in visibility that may not be perceptible. This is quite plausible if individuals are aware that many regulations lead to small improvements in visibility which when considered together amount to perceptible changes in visibility.

^z The Clean Air Act designates 156 national parks and wilderness areas as Class I areas for visibility protection.

^{aa} For details of the visibility estimates discussed in this chapter, please refer to the benefits technical support document for this RIA (Abt Associates 2000).

^{bb} An SAB advisory letter indicates that "many members of the Council believe that the Chestnut and Rowe study is the best available." (EPA-SAB-COUNCIL-ADV-00-002, 1999) However, the committee did not formally approve use of these estimates because of concerns about the peer-reviewed status of the study. EPA believes the study has received adequate review and has been cited in numerous peer-reviewed publications

essential input to our estimates of the benefits of recreational visibility improvements in the primary benefits estimates. Consistent with SAB advice, EPA has designated the McClelland, et al. study as significantly less reliable for regulatory benefit-cost analysis, although it does provide useful estimates on the order of magnitude of residential visibility benefits (EPA-SAB-COUNCIL-ADV-00-002, 1999). Residential visibility benefits are therefore only included as an alternative calculation in Table VII-25. The methodology for this alternative calculation, explained below, is similar to the procedure for recreational benefits.

The Chestnut and Rowe study measured the demand for visibility in Class I areas managed by the National Park Service (NPS) in three broad regions of the country: California, the Southwest, and the Southeast. Respondents in five states were asked about their willingness to pay to protect national parks or NPS-managed wilderness areas within a particular region. The survey used photographs reflecting different visibility levels in the specified recreational areas. The visibility levels in these photographs were later converted to deciviews for the current analysis. The survey data collected were used to estimate a WTP equation for improved visibility. In addition to the visibility change variable, the estimating equation also included household income as an explanatory variable.

The Chestnut and Rowe study did not measure values for visibility improvement in Class I areas outside the three regions. Their study covered 86 of the 156 Class I areas in the U.S. We can infer the value of visibility changes in the other Class I areas by transferring values of visibility changes at Class I areas in the study regions. However, these values are not as defensible and are thus presented only as an alternative calculation in Table VII-25. A complete description of the benefits transfer method used to infer values for visibility changes in Class I areas outside the study regions is provided in the benefits TSD for this RIA (Abt Associates, 2000).

The estimated relationship from the Chestnut and Rowe study is only directly applicable to the populations represented by survey respondents. EPA used benefits transfer methodology to extrapolate these results to the population affected by the final HD Engine/Diesel Fuel rule. A general willingness to pay equation for improved visibility (measured in deciviews) was developed as a function of the baseline level of visibility, the magnitude of the visibility improvement, and household income. The behavioral parameters of this equation were taken from analysis of the Chestnut and Rowe data. These parameters were used to calibrate WTP for the visibility changes resulting from the final HD Engine/Diesel Fuel rule. The method for developing calibrated WTP functions is based on the approach developed by Smith, et al. (1999). Available evidence indicates that households are willing to pay more for a given visibility improvement as their income increases (Chestnut, 1997). The benefits estimates here incorporate Chestnut's estimate that a 1 percent increase in income is associated with a 0.9 percent increase in WTP for a given change in visibility.

(Chestnut and Dennis, 1997).

Using the methodology outlined above, EPA estimates that the total WTP for the visibility improvements in California, Southwestern, and Southeastern Class I areas brought about by the final HD Engine/Diesel Fuel rule is \$3.3 billion. This value includes the value to households living in the same state as the Class I area as well as values for all households in the U.S. living outside the state containing the Class I area, and the value accounts for growth in real income.

For the alternative calculation for residential visibility, the McClelland, et al. study's results were used to calculate the parameter to measure the effect of deciview changes on WTP. The WTP equation was then run for the population affected by the final HD Engine/Diesel Fuel rule. The results indicate that improvements to residential visibility provide an economic benefit of \$ 2.1 billion dollars for the continental U.S.^{cc}

One major source of uncertainty for the visibility benefit estimate is the benefits transfer process used. Judgments used to choose the functional form and key parameters of the estimating equation for willingness to pay for the affected population could have significant effects on the size of the estimates. Assumptions about how individuals respond to changes in visibility that are either very small, or outside the range covered in the Chestnut and Rowe study, could also affect the results.

2. Agricultural and Forestry Benefits

The Ozone Criteria Document notes that “ozone affects vegetation throughout the United States, impairing crops, native vegetation, and ecosystems more than any other air pollutant” (US EPA, 1996). Reduced levels of ground-level ozone resulting from the final HD Engine/Diesel Fuel rule will have generally beneficial results on agricultural crop yields and commercial forest growth.

Well-developed techniques exist to provide monetary estimates of these benefits to agricultural and silvicultural producers and to consumers. These techniques use models of planting decisions, yield response functions, and agricultural and forest products supply and demand. The resulting welfare measures are based on predicted changes in market prices and production costs.

a. Agricultural Benefits

Laboratory and field experiments have shown reductions in yields for agronomic crops exposed to ozone, including vegetables (e.g., lettuce) and field crops (e.g., cotton and wheat). The most extensive field experiments, conducted under the National Crop Loss Assessment

^{cc} The McClelland, et al. (1993) study examined visibility changes in two Eastern cities, Chicago and Atlanta. Transferring these values to residential visibility changes in the Western U.S. may introduce greater uncertainty than transferring the values to other Eastern cities. As such, an additional alternate calculation showing the value of residential visibility just for the Eastern U.S. is included in Table VII-25.

Network (NCLAN) examined 15 species and numerous cultivars. The NCLAN results show that “several economically important crop species are sensitive to ozone levels typical of those found in the U.S.” (US EPA, 1996). In addition, economic studies have shown a relationship between observed ozone levels and crop yields (Garcia, et al., 1986). The economic value associated with varying levels of yield loss for ozone-sensitive commodity crops is analyzed using the AGSIM[®] agricultural benefits model (Taylor, et al., 1993). AGSIM[®] is an econometric-simulation model that is based on a large set of statistically estimated demand and supply equations for agricultural commodities produced in the United States. The model is capable of analyzing the effects of changes in policies (in this case, the implementation of the final HD Engine/Diesel Fuel rule) that affect commodity crop yields or production costs.^{dd}

The measure of benefits calculated by the model is the net change in consumer and producer surplus from baseline ozone concentrations to the ozone concentrations resulting from attainment of particular standards. Using the baseline and post-control equilibria, the model calculates the change in net consumer and producer surplus on a crop-by-crop basis.^{ee} Dollar values are aggregated across crops for each standard. The total dollar value represents a measure of the change in social welfare associated with the final HD Engine/Diesel Fuel rule.

The model employs biological exposure-response information derived from controlled experiments conducted by the NCLAN (NCLAN, 1996). For the purpose of our analysis, we analyze changes for the six most economically significant crops for which C-R functions are available: corn, cotton, peanuts, sorghum, soybean, and winter wheat.^{ff} For some crops there are multiple C-R functions, some more sensitive to ozone and some less. Our primary estimate assumes that crops are evenly mixed between relatively sensitive and relatively insensitive varieties. The primary estimate of the net change in economic surplus resulting from changes in ozone associated with the HD Engine/Diesel Fuel rule is \$1.1 billion (1999\$).

b. Forestry Benefits

Ozone also has been shown conclusively to cause discernible injury to forest trees (US EPA, 1996; Fox and Mickler, 1996). In this section, we describe methods for benefits we are able to quantify and we present a qualitative description of benefits we are not able to quantify at this time. For commercial forestry impacts, the effects of changes in ozone concentrations on tree growth for a limited set of species are predicted. For future analyses, it would be helpful to use

^{dd}AGSIM[®] is designed to forecast agricultural supply and demand out to 2010. We were not able to adapt the model to forecast out to 2030. Instead, we apply percentage increases in yields from decreased ambient ozone levels in 2030 to 2010 yield levels, and input these into an agricultural sector model held at 2010 levels of demand and supply. It is uncertain what impact this assumption will have on net changes in surplus.

^{ee} Agricultural benefits differ from other health and welfare endpoints in the length of the assumed ozone season. For agriculture, the ozone season is assumed to extend from April to September. This assumption is made to ensure proper calculation of the ozone statistic used in the exposure-response functions. The only crop affected by changes in ozone during April is winter wheat.

^{ff} The total value for these crops in 1998 was \$47 billion.

econometric models of forest product supply and demand to estimate changes in prices, producer profits and consumer surplus. However, for this RIA we were not able to monetize the biological changes we predicted for commercial tree species. For commercial forestry, well-developed techniques are used to estimate biological and market changes. Limitations of the approach presented here include: the lack of underlying forest inventory information which is not available for the Western U.S., and the unavailability of parameterization data for all relevant species nationally. Thus, we must assume that no ozone-related changes occur to forest inventories in the Western U.S. or Canada, although as described earlier, it is likely that across the country, this rulemaking could result in decreases in ozone and improvements in forest health compared to baseline conditions. Therefore, using these assumptions will underestimate the commercial forestry benefits associated with the program.

Similar to the agriculture analysis, assessing the forestry benefits couples air quality modeling results, C-R functions derived from a biological model, forest inventory estimates, and an economic model. Again, we are only able to quantify the physical effect, and further details are contained in the technical support document (Hubbell et al., 2000).

Our analysis used species-specific C-R functions derived from the TREGRO model (Laurence, et al., 2000). We developed ozone C-R functions for 6 species for which there were parameterization data by climatic region of the Eastern U.S.: black cherry, loblolly pine, red oak, red spruce, sugar maple, and tulip poplar. TREGRO is a model of tree physiological response to environmental stresses (Weinstein and Yanai, 1994). It was developed to simulate the response of sapling and mature trees to ozone and acidic precipitation stress in conjunction with other stressors. The model has been used to evaluate long-term effects of pollutants on resource availability.

The next step would be to use economic model such as the Timber Assessment Market Model (TAMM)/Aggregated Timberland Assessment System (ATLAS). In brief, the approach would be to use the biological inputs to modify the accumulation of inventory within ATLAS, which then shifts the timber supply functions in TAMM. The economic value of yield changes for commercial forests would be estimated using TAMM. This model is a US Forest Service (Adams and Haynes, 1996) spatial model of the solid wood and timber inventory elements of the U.S. forest products sector. The model provides projections of timber markets by geographic region and wood type through the year 2050. Nine regions covering the continental U.S. are included in the analysis; however, the effects of reduced O₃ concentrations were only considered for the Eastern U.S. The TAMM model perturbs timber market (spatial) equilibrium and yields timber price, quantity and welfare effects. However, it is limited to sawtimber and does not capture all relevant forest product markets (e.g., pulp wood). TAMM, in turn, would predict the effect of these reductions on timber markets by changing the annual growth rates of commercial forest growing-stock inventories. The model uses applied welfare economics to value changes in ambient O₃ concentrations. However, we were not able to complete this step for the RIA.

The six species we analyzed account for as much as 73 percent and as little as zero percent of total growing stock volume depending on the region and forest type. The annual change in growth adjustment factors ranged from zero to 0.009841. While the adjustment factor

may seem small on an absolute basis, when compounded over the lifetime of a tree, the effects may be significant. The full set of adjustment factors are presented in the technical support document (Hubbell et al., 2000).

c. Other Effects

An additional welfare benefit expected to accrue as a result of reductions in ambient ozone concentrations in the U.S. is the economic value the public receives from reduced aesthetic injury to forests. There is sufficient scientific information available to reliably establish that ambient ozone levels cause visible injury to foliage and impair the growth of some sensitive plant species (US EPA, 1996c, p. 5-521). However, present analytic tools and resources preclude EPA from quantifying the benefits of improved forest aesthetics.

Urban ornamentals represent an additional vegetation category likely to experience some degree of negative effects associated with exposure to ambient ozone levels and likely to impact large economic sectors. In the absence of adequate exposure-response functions and economic damage functions for the potential range of effects relevant to these types of vegetation, no direct quantitative economic benefits analysis has been conducted. It is estimated that more than \$20 billion (1990 dollars) are spent annually on landscaping using ornamentals (Abt Associates, 1995), both by private property owners/tenants and by governmental units responsible for public areas. This is therefore a potentially important welfare effects category. However, information and valuation methods are not available to allow for plausible estimates of the percentage of these expenditures that may be related to impacts associated with ozone exposure.

The final HD Engine/Diesel Fuel rule, by reducing NO_x emissions, will also reduce nitrogen deposition on agricultural land and forests. There is some evidence that nitrogen deposition may have positive effects on agricultural output through passive fertilization. Holding all other factors constant, farmers' use of purchased fertilizers or manure may increase as deposited nitrogen is reduced. Estimates of the potential value of this possible increase in the use of purchased fertilizers are not available, but it is likely that the overall value is very small relative to other health and welfare effects. The share of nitrogen requirements provided by this deposition is small, and the marginal cost of providing this nitrogen from alternative sources is quite low. In some areas, agricultural lands suffer from nitrogen over-saturation due to an abundance of on-farm nitrogen production, primarily from animal manure. In these areas, reductions in atmospheric deposition of nitrogen from PM represent additional agricultural benefits.

Information on the effects of changes in passive nitrogen deposition on forests and other terrestrial ecosystems is very limited. The multiplicity of factors affecting forests, including other potential stressors such as ozone, and limiting factors such as moisture and other nutrients, confound assessments of marginal changes in any one stressor or nutrient in forest ecosystems. However, reductions in deposition of nitrogen could have negative effects on forest and vegetation growth in ecosystems where nitrogen is a limiting factor (US EPA, 1993).

On the other hand, there is evidence that forest ecosystems in some areas of the United States are nitrogen saturated (US EPA, 1993). Once saturation is reached, adverse effects of additional nitrogen begin to occur such as soil acidification which can lead to leaching of nutrients needed for plant growth and mobilization of harmful elements such as aluminum. Increased soil acidification is also linked to higher amounts of acidic runoff to streams and lakes and leaching of harmful elements into aquatic ecosystems.

3. Benefits from Reductions in Materials Damage

The final HD Engine/Diesel Fuel rule is expected to produce economic benefits in the form of reduced materials damage. There are two important categories of these benefits. Household soiling refers to the accumulation of dirt, dust, and ash on exposed surfaces. Criteria pollutants also have corrosive effects on commercial/industrial buildings and structures of cultural and historical significance. The effects on historic buildings and outdoor works of art are of particular concern because of the uniqueness and irreplaceability of many of these objects.

Previous EPA benefit analyses have been able to provide quantitative estimates of household soiling damage. Consistent with SAB advice, we determined that the existing data (based on consumer expenditures from the early 1970's) are too out of date to provide a reliable enough estimate of current household soiling damages (EPA-SAB-Council-ADV-003, 1998). An estimate is included in the alternative calculations presented in Table VII-25.

EPA is unable to estimate any benefits to commercial and industrial entities from reduced materials damage. Nor is EPA able to estimate the benefits of reductions in PM-related damage to historic buildings and outdoor works of art. Existing studies of damage to this latter category in Sweden (Grosclaude and Soguel, 1994) indicate that these benefits could be an order of magnitude larger than household soiling benefits.

4. Benefits from Reduced Ecosystem Damage

The effects of air pollution on the health and stability of ecosystems are potentially very important, but are at present poorly understood and difficult to measure. The reductions in NO_x caused by the final rule could produce significant benefits. Excess nutrient loads, especially of nitrogen, cause a variety of adverse consequences to the health of estuarine and coastal waters. These effects include toxic and/or noxious algal blooms such as brown and red tides, low (hypoxic) or zero (anoxic) concentrations of dissolved oxygen in bottom waters, the loss of submerged aquatic vegetation due to the light-filtering effect of thick algal mats, and fundamental shifts in phytoplankton community structure (Bricker et al., 1999).

Reductions in nitrogen loadings are estimated for twelve eastern estuaries (including two on the Gulf Coast). These estimated reductions are described earlier in this Chapter. Four of these estuaries have established consensus goals for reductions in annual nitrogen loads, indicating an intention of reaching these goals through implementation of controls on nitrogen sources. These four estuaries and their reduction goals are listed in Table VII-20.

Table VII-20. Reduction Goals and 1998 Nitrogen Loads to Selected Eastern Estuaries (tons per year)

Estuary	Total Nitrogen Loadings	Nitrogen Loadings from Atmospheric Deposition	Overall Reduction Goal
Albemarle/Pamlico Sound	25,300	11,000	7,600
Chesapeake Bay	185,000	49,500	35,600
Long Island Sound	53,700	13,200	31,460
Tampa Bay	3,900	2,100	100

Source: US EPA, 1998.

Estimated reductions in deposition of atmospheric nitrogen to these four estuaries are listed in Table VII-21, along with the percentage of the reduction goal accounted for by these reductions. These figures suggest that the reductions in nitrogen deposition resulting from the final HD Engine/Diesel Fuel rule will provide significant progress towards meeting nitrogen reduction goals in several of these estuaries.

Table VII-21. Estimated Annual Reductions in Nitrogen Loadings in Selected Eastern Estuaries for the Final HD Engine/Diesel Fuel Rule in 2030 (tons per year)

Estuary	Change in Nitrogen Loadings	% of Estuary Nitrogen Reduction Goal
Albemarle/Pamlico Sound	1,804	23.7%
Chesapeake Bay	2,706	7.6%
Long Island Sound	1,067	3.4%
Tampa Bay ^A	385	over 100%

^A Tampa Bay had a very low nitrogen loadings reduction goal. As such, the HD Engine/Diesel Fuel rule provides more reductions than are necessary to achieve the stated goal.

Direct C-R functions relating changes in nitrogen loadings to changes in estuarine benefits are not available. The preferred WTP based measure of benefits depends on the availability of these C-R functions and on estimates of the value of environmental responses. Because neither appropriate C-R functions nor sufficient information to estimate the marginal value of changes in water quality exist at present, calculation of a WTP measure is not possible. An alternative is to use an avoided cost approach to estimate the welfare effects of PM on estuarine ecosystems. The use of the avoided cost approach to establish the value of a reduction in nitrogen deposition is problematic if there is not a direct link between reductions in air

deposited nitrogen and the abandonment of a costly regulatory program. However, there are currently no readily available alternatives to this approach.

Based on SAB advice, we use the avoided cost approach only to derive an alternative calculation of the value of reductions in atmospheric nitrogen loadings to estuaries (EPA-SAB-COUNCIL-ADV-00-002, 1999). The SAB believes that the avoided cost approach for nitrogen loadings is valid only if the state and local governments have established firm pollution reduction targets, and that displaced costs measured in the study represent measures not taken because of the Clean Air Act (EPA-SAB-COUNCIL-ADV-00-002, 1999). Because the nitrate reduction targets in the studied estuaries are not firm targets, and there is not assurance that planned measures would be undertaken in the absence of the Clean Air Act, we are currently unable to provide a meaningful primary estimate. Thus, the avoided cost estimate is presented as an alternative calculation in Table VII-25.

If better models of ecological effects can be defined, EPA believes that progress can be made in estimating WTP measures for ecosystem functions. These estimates would be superior to avoided cost estimates in placing economic values on the welfare changes associated with air pollution damage to ecosystem health. For example, if nitrogen or sulfate loadings can be linked to measurable and definable changes in fish populations or definable indexes of biodiversity, then CV studies can be designed to elicit individuals' WTP for changes in these effects. This is an important area for further research and analysis, and will require close collaboration among air quality modelers, natural scientists, and economists.

5. Estimated Values for Welfare Endpoints

Applying the valuation methods described above to the estimated changes in ozone and PM in 2030 yields estimates of the value of changes in visibility and agricultural and forestry yields. These estimates are presented in Table VII-22. All of the monetary benefits are in constant 1999 dollars.

We are unable to provide primary monetized estimates of residential visibility, household soiling, materials damage, and nitrogen deposition, in addition to the other welfare effects listed in Table VII-1. These unmonetized benefits are indicated by placeholders, labeled B_5 to B_{12} . The estimate of total monetized welfare benefits is thus equal to the subset of monetized welfare benefits plus B_w , the sum of the unmonetized welfare benefits.

Table VII-22. Primary Estimate of Annual Monetary Values for Welfare Effects Associated With Improved Air Quality Resulting from the HD Engine/Diesel Fuel Rule in 2030

Endpoint	Monetary Benefits (millions 1999\$, Unadjusted for growth in real income) ^A	Monetary Benefits (millions 1999\$, Adjusted for Growth in Real Income) ^A
<i>PM-related Endpoints</i>		
Recreational Visibility (86 Class I areas in California, the Southeast and the Southwest)	\$1,790	\$3,260
Residential Visibility	B ₅	B ₅
Household Soiling	B ₆	B ₆
Materials Damage	B ₇	B ₇
Nitrogen Deposition to Estuaries	B ₈	B ₈
Other PM-related welfare effects ^B	B ₉	B ₉
<i>Ozone-related Endpoints</i>		
Commercial Agricultural Benefits (6 major crops) (Eastern U.S. only) ^C	\$1,120	\$1,120
Commercial Forestry Benefits (Eastern U.S. only) ^C	B ₉	B ₉
Other ozone-related welfare effects ^B	B ₁₀	B ₁₀
CO-related welfare effects ^B	B ₁₁	B ₁₁
NMHC-related welfare effects ^B	B ₁₂	B ₁₂
<i>Total Monetized Welfare-related Benefits^D</i>	\$2,910	\$4,380

^A Rounded to the nearest 10 million and visibility benefits are adjusted to account for growth in real GDP per capita between 1990 and 2030.

See Section C. ^B A detailed listing of unquantified PM, ozone, CO, and NMHC related welfare effects is provided in Table VII-1.

^C Ozone-related benefits are only calculated for the Eastern U.S. due to unavailability of reliable modeled ozone concentrations in the Western U.S. This results in an underestimate of national ozone-related benefits. See Section D-3 for a detailed discussion of the UAM-V ozone model and model performance issues. ^D B_w is equal to the sum of all unmonetized welfare categories, i.e. B₅+B₆+...+B₁₃.

Total monetized welfare-related benefits are around \$4.4 billion. Monetized welfare benefits are roughly 1/20th the magnitude of monetized health benefits. However, due to the difficulty in quantifying and monetizing welfare benefits, a higher proportion of welfare benefits are not monetized. It is thus inappropriate to conclude that welfare benefits are unimportant just by comparing the estimates of the monetized benefits. Also, as with health benefits, ozone-related welfare benefits may be significantly underestimated due to the omission of ozone-related benefits in the Western U.S.

Alternative calculations for recreational visibility, residential visibility, household soiling, and nitrogen deposition are presented in Table VII-25 later in this chapter.

F. Total Benefits

We provide our primary estimate of benefits for each health and welfare endpoint as well as the resulting primary estimate of total benefits. To obtain this estimate, we aggregate dollar benefits associated with each of the effects examined, such as hospital admissions, into a total benefits estimate assuming that none of the included health and welfare effects overlap. The primary estimate of the total benefits associated with the health and welfare effects is the sum of the separate effects estimates. Total monetized benefits associated with the final HD Engine/Diesel Fuel rule are listed in Table VII-23, along with a breakdown of benefits by endpoint. Note that the value of endpoints known to be affected by ozone and/or PM that we are not able to monetize are assigned a placeholder value (e.g., B_1 , B_2 , etc.). Unquantified physical effects are indicated by a U. The estimate of total benefits is thus the sum of the monetized benefits and a constant, B, equal to the sum of the unmonetized benefits, $B_1+B_2+\dots+B_n$.

A comparison of the incidence column to the monetary benefits column reveals that there is not always a close correspondence between the number of incidences avoided for a given endpoint and the monetary value associated with that endpoint. For example, there are over 40 times more asthma attacks than premature mortalities, yet these asthma attacks account for only a very small fraction of total monetized benefits. This reflects the fact that many of the less severe health effects, while more common, are valued at a lower level than the more severe health effects. Also, some effects, such as asthma attacks, are valued using a proxy measure of WTP. As such the true value of these effects may be higher than that reported in Table VII-23.

Our primary estimate of total monetized benefits for the final HD Engine/Diesel Fuel rule is \$70.4 billion, of which \$62.6 billion is the benefits of reduced premature mortality risk from PM exposure. Total monetized benefits are dominated by the benefits of reduced mortality risk. Mortality related benefits account for 89 percent of total monetized benefits followed by recreational visibility (4.6 percent) and chronic bronchitis (3.5 percent). Health benefits account for 94 percent of total benefits.

Table VII-23. Primary Estimate of Annual Monetized Benefits Associated With Improved Air Quality Resulting from the HD Engine/Diesel Fuel Rule in 2030^{A,B}

Endpoint	Pollutant	Avoided Incidence ^C (cases/year)	Monetary Benefits ^D (millions 1999\$, Adjusted for Income Growth)
Premature mortality ^E (adults, 30 and over)	PM	8,300	\$62,580
Chronic bronchitis (adults, 26 and over)	PM	5,500	\$2,430
Hospital Admissions from Respiratory Causes	O ₃ and PM	4,100	\$60
Hospital Admissions from Cardiovascular Causes	O ₃ and PM	3,000	\$50
Emergency Room Visits for Asthma	O ₃ and PM	2,400	<\$5
Acute bronchitis (children, 8-12)	PM	17,600	<\$5
Lower respiratory symptoms (children, 7-14)	PM	192,900	<\$5
Upper resp. symptoms (asthmatic children, 9-11)	PM	193,400	\$10
Asthma attacks (asthmatics, all ages) ^F	O ₃ and PM	361,400	B _a
Work loss days (adults, 18-65)	PM	1,539,400	\$160
Minor restricted activity days (adults, age 18-65)	O ₃ and PM	9,838,500	\$530
Other health effects ^{F,G}	O ₃ , PM, CO, HAPs	U ₁ +U ₂ +U ₃ +U ₄	B ₁ +B ₂ +B ₃ +B ₄
Decreased worker productivity	O ₃	—	\$140
Recreational visibility (86 Class I Areas)	PM	—	\$3,260
Residential visibility	PM	—	B ₅
Household soiling damage	PM	—	B ₆
Materials damage	PM	—	B ₇
Nitrogen Deposition to Estuaries	Nitrogen	—	B ₈
Agricultural crop damage (6 crops)	O ₃	—	\$1,120
Commercial forest damage (6 species)	O ₃	—	B ₉
Other welfare effects ^{F,G}	O ₃ , PM, CO, HAPs	—	B ₁₀ +B ₁₁ +B ₁₂ +B ₁₃
Monetized Total ^H			\$70,360+B

^A Monetary benefits are adjusted to account for growth in real GDP per capita between 1990 and 2030. See Section C. ^B Ozone-related benefits are only calculated for the Eastern U.S. due to unavailability of reliable modeled ozone concentrations in the Western U.S. This results in an underestimate of national ozone-related benefits. See Section D-3 for a detailed discussion of the UAM-V ozone model and model performance issues. ^C Incidences are rounded to the nearest 100. ^D Dollar values are rounded to the nearest 10 million. ^E Premature mortality associated with ozone is not separately included in this analysis. It is assumed that the Section D-3 ACS/Krewski et al., 2000 C-R function for premature mortality captures both PM mortality benefits and any mortality benefits associated with other air pollutants. Also note that the valuation assumes the 5 year distributed lag structure described earlier. ^F The U_i are the incidences for the unquantified category i, the B_i are the monetary values for the unquantified endpoint i. For some categories such as asthma attacks, we were able to quantify the reduction in incidence, but we present the monetization as an alternative calculation. ^G A detailed listing of unquantified PM, ozone, CO, and NMHC related health and welfare effects is provided in Table VII-1. ^H B is equal to the sum of all unmonetized categories, i.e. B_a+B₁+B₂+...+B₁₃.

As discussed in Section C.1, we have adjusted our primary estimate of benefits to reflect the projected growth in real income between base income in 1990 and the 2030 analytical year. We account for real income growth by applying the primary adjustment factors from Table VII-12 to the appropriate health and welfare endpoints in Tables VII-19 and VII-22.

In addition to the primary estimate in Table VII-23, in Tables VII-24 and VII-25 we present alternative calculations representing how the value for individual endpoints or total benefits would change if we were to make a different assumption about an element of the benefits analysis. Specifically, in Table VII-24, we present the impact of different C-R functions for PM-related premature mortality. In Table VII-25, we show the impact of alternative assumptions about other parameters. For example, Table VII-25 can be used to answer questions like “What would total benefits be if we were to value avoided incidences of premature mortality using the VS LY approach rather than the VSL approach?” This table provides alternative calculations both for valuation issues (e.g. the correct value for a statistical life saved) and for physical effects issues (e.g., possible recovery from chronic illnesses). This table is not meant to be comprehensive. Rather, it reflects some of the key issues identified by EPA or commentors as likely to have a significant impact on total benefits. As discussed earlier, individual adjustments in the table should not be added together without addressing potential issues of overlap and low joint probability among the endpoints. Accompanying Table VII-25 is a brief discussion of each of the alternative calculations.

While Tables VII-24 and VII-25 provide alternative calculations for specific alternative assumptions, there are some parameters to which total benefits may be sensitive but for which no or limited credible scientific information exists to determine plausible values. Sensitivity analyses for these parameters are presented in Appendix VII-A. Issues examined in this appendix include alternative specifications for the lag structure of PM related premature mortality and impacts of assumed thresholds on the estimated incidence of avoided premature mortality. This appendix also contains several illustrative endpoint calculations for which the scientific uncertainty is too great to provide a reasonable estimate and if included, might lead to double-counting of benefits. These include premature mortality associated with daily fluctuations in PM, infant mortality associated with PM, and premature mortality associated with daily fluctuations in ozone.

Table VII-24. Alternative Estimates of Premature Mortality Benefits for the HD Engine/Diesel Fuel Rule in 2030

	Model	Avoided Incidences	Value Adjusted for Growth in Real Income (million 1999\$)	Impact on Primary Benefits Estimate Adjusted for Growth in Real Income (million 1999\$)
1	Fine Particles Alone, Random Effects, Regional Adjustment Source: Table 46, Krewski, et al. (2000) "ACS Study"	9,400	\$69,940	+\$7,370 (+10.5%)
2	Fine Particles Alone, Random Effects, Independent Cities Source: Table 46, Krewski, et al. (2000) "ACS Study"	16,000	\$93,940	+\$59,270 (+84.2%)
3	All Combined, All Cause, Fine Particles Source: Table 3, Pope, et al. (1995) "ACS Study"	9,900	\$75,360	+12,780 (+18.2%)
4	All Causes, Extended, Age Time Axis Source: Table 3, Krewski, et al. (2000) "Harvard Six-city Study"	24,200	\$181,080	+\$118,500 (+168.4%)
5	All Subjects Source: Table 3, Dockery, et al. (1993) "Harvard Six-city Study"	23,100	\$173,450	+\$110,874 (+157.6%)

^A Reported relative risks for the Pope, et al. (1995) and Dockery, et al. (1993) studies are comparisons of mortality rates between most polluted and least polluted cities. For the Pope et al. study the relative risk is based on a difference in median PM_{2.5} levels of 24.5 µg/m³. For the Dockery et al. study, the relative risk is based on a difference of 18.6 µg/m³. The Krewski et al. reanalysis of the Pope et al. study reports all relative risks based on a 24.5 µg/m³ difference for comparability with the Pope, et al. (1995) results, rather than comparing the means or medians of the most polluted and least polluted studies. Likewise, the Krewski et al. reanalysis of the Dockery et al. Harvard Six Cities study reports all relative risks based on a 18.6 µg/m³ difference for comparability with the Dockery, et al. (1993) study.

^B Assumes national all-cause mortality rate of 0.0147 per person for adults aged 30 and older and 0.0131 per person for adults aged 25 and older. (U.S. Centers for Disease Control. 2000 *National Vital Statistics Reports* 48(11): Table 8).

The first alternative C-R function (row 1 of Table VII-24) is based on the relative risk of 1.16 from the "Fine Particles Alone, Regional Adjustment Random Effects" model reported in Table 46 of the HEI report. This C-R function is a reasonable specification to explore the impact of adjustments for broad regional correlations. However, the HEI report noted that the spatial adjustment methods "may have over adjusted the estimated effect for regional pollutants such as fine particles and sulfate compared with the effect estimates for more local pollutants such as sulfur dioxide." Thus, the estimates of avoided incidences of premature mortality based on this C-R function may underestimate the true effect. Note that this C-R function is based on the original air quality dataset used in the ACS study, covering 50 cities, and used the median PM_{2.5} levels rather than mean PM_{2.5} as the indicator of exposure.

Krewski, et al. (2000) also estimated a random effects model which accounts for between city variation but “ignores possible regional patterns in mortality.” The estimated avoided incidences of premature mortality is based on the original 50 city air quality dataset used in the ACS study and used the median $PM_{2.5}$ levels rather than mean $PM_{2.5}$ as the indicator of exposure (row 2 of Table VII-24).

For comparison with earlier benefits analyses, we also include estimates of avoided incidences of premature mortality based on the original ACS/Pope et al. (1995) analysis (row 3 of Table VII-24) and the original “Harvard Six Cities” estimate as reported in Dockery, et al. (1993) analysis (row 5 of Table VII-24).

The Krewski, et al. “Harvard Six Cities” estimate of the relationship between PM exposure and premature mortality (row 4 of Table VII-24) is a plausible alternative to the Krewski, et al. “ACS 50 City” primary estimate. The SAB has noted that “the [Harvard Six Cities] study had better monitoring with less measurement error than did most other studies” (EPA-SAB-COUNCIL-ADV-99-012, 1999). However, the Krewski-Harvard Six Cities study had a more limited geographic scope (and a smaller study population) than the Krewski-ACS study. The demographics of the ACS study population, i.e., largely white and middle-class, may also produce a downward bias in the estimated PM mortality coefficient, because short-term studies indicate that the effects of PM tend to be significantly greater among groups of lower socioeconomic status. The Krewski-Harvard Six Cities study also covered a broader age category (25 and older compared to 30 and older in the ACS study) and followed the cohort for a longer period (15 years compared to 8 years in the ACS study). For these reasons, the Krewski-Harvard Six Cities study is considered to be a plausible alternative estimate of the avoided premature mortality incidences associated with the final HD Engine/Diesel Fuel rule.

**Table VII-25. Additional Alternative Benefits Calculations
for the HD Engine/Diesel Fuel Rule in 2030**

Alternative Calculation	Description of Estimate	Impact on Primary Benefit Estimate Adjusted for Growth in Real Income (million 1999\$)
1	Value of avoided premature mortality incidences based on age-specific VSL	Calculate the age distribution of avoided incidences of premature mortality and apply age-adjusted VSL to the incidences. Sources of age-adjustment ratios are Jones-Lee (1989) and Jones-Lee et al. (1993)
		Jones-Lee (1989) -\$28,510 (-40.5%)
		Jones-Lee (1993) -\$6,820 (-10.0%)
2	Chronic Asthma	Avoided incidences of chronic asthma are estimated using the McDonnell, et al. (1999) C-R function. The number of avoided incidences of chronic asthma is 820.
		+\$40 (+<1%)
3	Reversals in chronic bronchitis treated as lowest severity cases	Instead of omitting cases of chronic bronchitis that reverse after a period of time, they are treated as being cases with the lowest severity rating. The number of avoided chronic bronchitis incidences increases from 5,480 to 10,250 (87%).
		+\$940 (+1.3%)
4	COPD and pneumonia hospital admissions.	Hospital admissions for Pneumonia and COPD estimated using the Moolgavkar (1997) C-R function instead of the Samet et al. (2000) pooled C-R function. The number of hospital admissions for these two causes decreases from 2,010 to 600 (-70%)
		-\$20 (<-1%)
5	Value of visibility changes in all Class I areas	Values of visibility changes at Class I areas in California, the Southwest, and the Southeast are transferred to visibility changes in Class I areas in other regions of the country.
		+\$1,240 (+1.8%)
6	Value of visibility changes in Eastern U.S. residential areas	Value of visibility changes outside of Class I areas are estimated for the Eastern U.S. based on the reported values for Chicago and Atlanta from McClelland et al. (1990).
		+\$1,250 (+1.8%)
7	Value of visibility changes in Western U.S. residential areas	Value of visibility changes outside of Class I areas are estimated for the Western U.S. based on the reported values for Chicago and Atlanta from McClelland et al. (1990).
		+\$910 (+1.3%)
8	Household soiling damage	Value of decreases in expenditures on cleaning are estimated using values derived from Manuel, et al. (1983).
		+\$260 (+0.4%)
9	Avoided costs of reducing nitrogen loadings in east coast estuaries	Estuarine benefits in 12 East coast estuaries from reduced atmospheric nitrogen deposition are approximated using the avoided costs of removing or preventing loadings from terrestrial sources.
		+\$150 (+0.3%)
10	Asthma attacks	Avoided incidences of asthma attacks monetized using Rowe and Chestnut (1986).
		+\$20 (+<1%)

The age-specific VSL alternative calculation (row 1 of Table VII-25) recognizes that individuals who die from air pollution related causes tend to be older than the average age of individuals in the VSL studies used to develop the \$6 million value. A complete discussion of this issue can be found in section 3.b of this chapter. For this calculation, the method we use to account for age differences is to adjust the VSL based on ratios of VSL's for specific ages to the VSL for a 40 year old individual (row 2 of Table VII-25). There are several potential sources for these ratios. Estimates from two Jones-Lee studies provide a reasonable low and high end for this type of adjustment. The ratios based on Jones-Lee (1989), as summarized in U.S. EPA (2000), suggest a steep inverted U shape between age and VSL, with the VSL for a 70 year old at 63 percent of that for a 40 year old, and the VSL for an 85 year old at 7 percent of that for 40 year old. The ratios based on Jones-Lee (1993) and summarized in U.S. EPA (2000b), suggest a much flatter inverted U shape, with the VSL for a 70 year old at 92 percent of that for a 40 year old, and the VSL for an 85 year old at 82 percent of that for a 40 year old. The general U shaped relationship is supported by recent analyses conducted in Canada and the U.S. by Krupnick et al. (2000a, 2000b). Their results suggest a curvature somewhere between the two Jones-Lee estimates. The wide range of age-adjustment ratios, especially at older ages demonstrates the difficulty in making these kinds of adjustments. To calculate the age-adjusted VSL, we first calculate the number of avoided premature mortalities in each age category, and then apply the age adjusted VSL to the appropriate incidences in each age category^{§§}.

The alternative calculation for the development of chronic asthma (row 2 of Table VII-25) is estimated using a recent study by McDonnell, et al. (1999) which found a statistical association between ozone and the development of asthma in adult white, non-Hispanic males. Other studies have not identified an association between air quality and the onset of asthma. Chronic asthma is characterized by repeated incidences of inflammation of the lungs. This causes restriction in the airways and results in shortness of breath, wheezing, and coughing. Asthma is also characterized by airway hyper responsiveness to stimuli. Chronic asthma affects over seven percent of the U.S. population (US Centers for Disease Control and Prevention, 1999b).

The McDonnell, et al. study is a prospective cohort analysis, measuring the association between long-term exposure to ambient concentrations of ozone and development of chronic asthma in adults. The study found a statistically significant effect for adult males, but none for adult females. EPA also believes it to be appropriate to apply the C-R function to all adult males over age 27 because no evidence exists to suggest that non-white adult males have a lower responsiveness to air-pollution. For other health effects such as shortness of breath, where the study population was limited to a specific group potentially more sensitive to air pollution than the general population (Ostro et al., 1995), EPA has applied the C-R function only to the limited population.

^{§§} The age categories and lower and upper end estimated age-adjustment ratios are: 30-39 (0.89, 0.98), 40-59 (1.0, 1.0), 60-69 (0.86, 0.97), 70-79 (0.63, 0.92), 80-84 (0.28, 0.85), 85+ (0.07, 0.82).

Some commentators have raised questions about the statistical validity of the associations found in this study and the appropriateness of transferring the estimated C-R function from the study populations (white, non-Hispanic males) to other male populations (i.e. African-American males). Some of these concerns include the following: 1) no significant association was observed for female study participants also exposed to ozone; 2) the estimated C-R function is based on a cross-sectional comparison of ozone levels, rather than incorporating information on ozone levels over time; 3) information on the accuracy of self-reported incidence of chronic asthma was collected but not used in estimating the C-R function; 4) the study may not be representative of the general population because it included only those individuals living 10 years or longer within 5 miles of their residence at the time of the study; and 5) the study had a significant number of study participants drop out, either through death, loss of contact, or failure to provide complete or consistent information. EPA believes that while these issues may result in increased uncertainty about this effect, none can be identified with a specific directional bias in the estimates. In addition, the SAB reviewed the study and deemed it appropriate for quantification of changes in ozone concentrations in benefits analyses (EPA-SAB-COUNCIL-ADV-00-001, 1999). EPA recognizes the need for further investigation by the scientific community to confirm the statistical association identified in the McDonnell, et al. study.

Following SAB advice (EPA-SAB-COUNCIL-ADV-00-001, 1999) and consistent with the Section 812 Prospective Report, we quantify this endpoint for the RIA. However, it should be noted that it is not clear that the intermittent, short-term, and relatively small changes in annual average ozone concentrations resulting from this rule alone are likely to measurably change long-term risks of asthma.

Similar to the valuation of chronic bronchitis, WTP to avoid chronic asthma is presented as the net present value of what would potentially be a stream of costs and lower well-being incurred over a lifetime. Estimates of WTP to avoid asthma are provided in two studies, one by Blumenschein and Johannesson (1998) and one by O’Conor and Blomquist (1997). Both studies use the contingent valuation method to solicit annual WTP estimates from individuals who have been diagnosed as asthmatics. The central estimate of lifetime WTP to avoid a case of chronic asthma among adult males, approximately \$25,000, is the average of the present discounted value from the two studies. Details of the derivation of this central estimate from the two studies is provided in the benefits TSD for this RIA (Abt Associates, 2000).

Another important issue related to chronic conditions is the possible reversal in chronic bronchitis incidences (row 3 of Table VII-25). Reversals are defined as those cases where an individual reported having chronic bronchitis at the beginning of the study period but reported not having chronic bronchitis in follow-up interviews at a later point in the study period. Since, by definition, chronic diseases are long-lasting or permanent, if the disease goes away it is not chronic. However, we have not captured the benefits of reducing incidences of bronchitis that are somewhere in-between acute and chronic. One way to address this is to treat reversals as cases of chronic bronchitis that are at the lowest severity level. These cases thus get the lowest value for chronic bronchitis.

For this benefits analysis, we have adopted the C-R function for COPD and pneumonia hospital admissions from Samet, et al. (2000). This estimate, while representing the state of the art in epidemiological studies, is a good deal larger than the estimate from Moolgavkar (1997). We explore the impact of using the Moolgavkar (1997) estimate instead of the Samet, et al. (2000) estimate in row 4 of Table VII-25.

The alternative calculation for recreational visibility (row 5 of Table VII-25) is an estimate of the full value of visibility in the entire region affected by the final HD Engine/Diesel Fuel rule. The Chestnut and Rowe study from which the primary valuation estimates are derived only examined WTP for visibility changes in the southeastern portion of the affected region. In order to obtain estimates of WTP for visibility changes in the northeastern and central portion of the affected region, we have to transfer the southeastern WTP values. This introduces additional uncertainty into the estimates. However, we have taken steps to adjust the WTP values to account for the possibility that a visibility improvement in parks in one region, is not necessarily the same environmental quality good as the same visibility improvement at parks in a different region. This may be due to differences in the scenic vistas at different parks, uniqueness of the parks, or other factors, such as public familiarity with the park resource. To take this potential difference into account, we adjusted the WTP being transferred by the ratio of visitor days in the two regions.

The alternative calculations for residential visibility (rows 6 and 7 of Table VII-25) are based on the McClelland, et al. study of WTP for visibility changes in Chicago and Atlanta. As discussed in Section F-1, SAB advised EPA that the residential visibility estimates from the available literature are inadequate for use in a primary estimate in a benefit-cost analysis. However, EPA recognizes that residential visibility is likely to have some value and the McClelland, et al. estimates are the most useful in providing an estimate of the likely magnitude of the benefits of residential visibility improvements.

The alternative calculation for household soiling (row 8 of Table VII-25) is based on the Manuel, et al. study of consumer expenditures on cleaning and household maintenance. This study has been cited as being “the only study that measures welfare benefits in a manner consistent with economic principals (Desvouges et al., 1998). However, the data used to estimate household soiling damages in the Manuel, et al. study are from a 1972 consumer expenditure survey and as such may not accurately represent consumer preferences in 2030. EPA recognizes this limitation, but believes the Manuel, et al. estimates are still useful in providing an estimate of the likely magnitude of the benefits of reduced PM household soiling.

The alternative calculation for the avoided costs of reductions in nitrogen loadings (row 9 of Table VII-25) is constructed by examining the avoided costs to surrounding communities of reduced nitrogen loadings for three case study estuaries (US EPA, 1998). The three case study estuaries are chosen because they have agreed upon nitrogen reduction goals and the necessary nitrogen control cost data. The values of atmospheric nitrogen reductions are determined on the basis of avoided costs associated with agreed upon controls of nonpoint water pollution sources. Benefits are estimated using a weighted-average, locally-based cost for nitrogen removal from water pollution (US EPA, 1998). Valuation reflects water pollution control cost avoidance based

on the weighted average cost per pound of current non-point source water pollution controls for nitrogen in the three case study estuaries. Taking the weighted cost per pound of these available controls assumes States will combine low cost and high cost controls, which could inflate avoided cost estimates. The avoided cost measure is likely to be an underestimate of the value of reduced nitrogen loadings in eastern estuaries because: 1) the 12 estuaries represent only about 50 percent of the total watershed area in the Eastern U.S.; and 2) costs avoided are not good proxies for WTP, understating true WTP under certain conditions.

We monetize the reduction of 361,400 asthma attacks (row 10 of Table VII-25) using Rowe and Chestnut (1986).

G. Comparison of Costs to Benefits

Benefit-cost analysis provides a valuable framework for organizing and evaluating information on the effects of environmental programs. When used properly, benefit-cost analysis helps illuminate important potential effects of alternative policies and helps set priorities for closing information gaps and reducing uncertainty. According to economic theory, the efficient policy alternative maximizes net benefits to society (i.e., social benefits minus social costs). However, not all relevant costs and benefits can be captured in any analysis. Executive Order 12866 clearly indicates that unquantifiable or nonmonetizable categories of both costs and benefits should not be ignored. There are many important unquantified and unmonetized costs and benefits associated with reductions in emissions, including many health and welfare effects. Potential benefit categories that have not been quantified and monetized are listed in Table VII-1 of this chapter.

In addition to categories that cannot be included in the calculated net benefits, there are also practical limitations for the comparison of benefits to costs in this analysis, as discussed throughout this chapter. Several specific limitations deserve to be mentioned again here:

- The state of atmospheric modeling is not sufficiently advanced to provide a workable “one atmosphere” model capable of characterizing ground-level pollutant exposure for all pollutants of interest (e.g., ozone, particulate matter, carbon monoxide, nitrogen deposition, etc). Therefore, the EPA must employ several different pollutant models to characterize the effects of alternative policies on relevant pollutants. Also, not all atmospheric models have been widely validated against actual ambient data. In particular, since the monitoring network for PM_{2.5} has produced only one year of data, atmospheric models designed to capture the effects of alternative policies on PM_{2.5} have not yet been fully validated. Additionally, significant shortcomings exist in the data that are available to perform these analyses. While containing identifiable shortcomings and uncertainties, EPA believes the models and assumptions used in the analysis are reasonable based on the available evidence.
- Another dimension adding to the uncertainty of this analysis is time. In our analysis we are projecting over a 30 year time period, which can introduce significant uncertainty.

Projected growth in factors such as population, income, source-level emissions, and vehicle miles traveled over the 30-year period have a significant effect on the benefits estimates, as will changes in health baselines, technology, and other factors. In addition, there is no clear way to predict future meteorological conditions compared to those used in these analyses. Again, EPA believes that the assumptions used to capture these elements are reasonable based on the available evidence..

- Qualitative and more detailed discussions of the above and other uncertainties and limitations are included in detail in earlier sections. Where information and data exist, quantitative characterizations of these uncertainties are included (in this chapter, the benefits TSD, and Appendix VII-A). However, data limitations prevent an overall quantitative estimate of the uncertainty associated with final estimates. Nevertheless, the reader should keep all of these uncertainties and limitations in mind when reviewing and interpreting the results.
- The primary benefit estimate does not include the monetary value of health benefits from ozone changes in the Western U.S. It also does not include the monetary value of several known ozone and PM-related welfare effects, including residential visibility, recreational visibility in over half of Federal Class I areas, agricultural and forestry benefits in the Western U.S. and for many crops and species, household soiling and materials damage, and deposition of nitrogen to sensitive estuaries.

Nonetheless, if one is mindful of these limitations, the relative magnitude of the benefit-cost comparison presented here can be useful information. Thus, this section summarizes the benefit and cost estimates that are potentially useful for evaluating the efficiency of the final HD Engine/Diesel Fuel rulemaking.

Our estimates of annual costs for this rulemaking are developed in Chapter V. As described in that chapter, at a 7 percent discount rate, the total program cost in 2030 is approximately **\$4.3 billion (1999\$)**. If a discount rate of 3% is used instead, this cost estimate drops to approximately **\$4.2 billion (1999\$)**. This latter value is used in our comparison of costs to benefits for calendar year 2030.

The primary estimate of monetized benefits is **\$70.4 billion (1999\$)**. Comparing this with costs of **\$4.2 billion (1999\$)**, monetized net benefits are approximately **\$66.2 billion (1999\$)**. Therefore, implementation of the HD Engine/Diesel Fuel program will provide society with a net gain in social welfare based on economic efficiency criteria. Table VII-26 summarizes the costs, benefits, and net benefits for the HD Engine/Diesel Fuel rule. Note that the cost and benefit estimates presented in Table VII-26 assume a 3 percent discount rate. Assuming a 7 percent discount rate does not materially alter the outcome. Net benefits are reduced by \$3.9 billion to \$62.3 billion, a reduction of 6 percent.

Table VII-26. 2030 Annual Monetized Costs, Benefits, and Net Benefits for the Final HD Engine/Diesel Fuel Rule

	Billions of 1999\$
Annual compliance costs	\$4.2
Monetized PM-related benefits^{B,C}	\$69.0 + B_{PM}
Monetized Ozone-related benefits^{B,D}	\$1.4 + B_{Ozone}
NMHC-related benefits	not monetized (B_{NMHC})
CO-related benefits	not monetized (B_{CO})
Total annual benefits	\$70.4 + B_{PM} + B_{Ozone} + B_{NMHC} + B_{CO}
Monetized net benefits^E	\$66.2 + B

^A For this section, all costs and benefits are rounded to the nearest 100 million. Thus, figures presented in this chapter may not exactly equal benefit and cost numbers presented in earlier sections of the chapter.

^B Not all possible benefits or disbenefits are quantified and monetized in this analysis. Potential benefit categories that have not been quantified and monetized are listed in Table VII-1. Unmonetized PM- and ozone-related benefits are indicated by **B_{PM}**. And **B_{Ozone}**, respectively.

^D Ozone-related benefits are only calculated for the Eastern U.S. due to unavailability of reliable modeled ozone concentrations in the Western U.S. This results in an underestimate of national ozone-related benefits. See US EPA (2000a) for a detailed discussion of the UAM-V ozone model and model performance issues.

^E **B** is equal to the sum of all unmonetized benefits, including those associated with PM, ozone, CO, and NMHC.

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Appendix VII-A: Supplementary Benefit Estimates and Sensitivity Analyses of Key Parameters in the Benefits Analysis

A. Introduction and Overview

In chapter VII, we estimated the benefits of the final HD Engine/Diesel Fuel rule using the most comprehensive set of endpoints available. For some health endpoints, this meant using a concentration-response (C-R) function that linked a larger set of effects to a change in pollution, rather than using C-R functions for individual effects. For example, the minor restricted activity day endpoint covers most of the symptoms used to characterize days of moderate or worse asthma and shortness of breath. For premature mortality, we selected a C-R function that captured reductions in incidences due to both long and short-term exposures to ambient concentrations of particulate matter (PM). In addition, the premature mortality C-R function is expected to capture at least some of the mortality effects associated with exposure to ozone. This ozone effect is described more fully below in section A.2.

In order to provide the reader with a fuller understanding of the health effects associated with reductions in air pollution associated with the final HD Engine/Diesel Fuel rule, this appendix provides estimates for those health effects which, if included in the primary estimate, could result in double-counting of benefits. For some endpoints, such as ozone mortality, additional research is needed to provide separate estimates of the effects for different pollutants, i.e. PM and ozone. These supplemental estimates should not be considered as additive to the primary estimate of benefits, but illustrative of these issues and uncertainties. Supplemental estimates included in this appendix include premature mortality associated with short-term exposures to PM and ozone, acute respiratory symptoms in adults, shortness of breath in asthmatic children, and occurrences of moderate or worse asthma symptoms in asthmatic adults. In addition, an estimate of the avoided incidences of premature mortality in infants is provided. Because the Pope, et al. estimate applies only to adults, avoided incidences of infant mortality are additive to the primary benefits estimate.

Tables VII-24 and VII-25 in Chapter VII reports the results of alternative calculations based on plausible alternatives to the assumptions used in deriving the primary estimate of benefits. In addition to these calculations, four important parameters, the length and structure of the potential lag in mortality effects, thresholds in PM health effects, discount rates, and the income elasticity of WTP have been identified as key to the analysis, and are explored in this appendix through the use of sensitivity analyses.

B. Supplementary Benefit Estimates

In the primary estimate, we use the Krewski, et al. (2000) study to provide the C-R function relating premature mortality to long-term PM exposure. The primary analysis assumes that this mortality occurs over a five year period, with 25 percent of the deaths occurring in the first year, 25 percent in the second year, and 16.7 percent in each of the third, fourth, and fifth years. Studies examining the relationship between short-term exposures and premature mortality can reveal what proportion of premature mortality is due to immediate response to daily variations in PM. There is only one short-term study (presenting results from 6 separate U.S. cities) that uses PM_{2.5} as the metric of PM (Schwartz et al., 1996). As such, the supplemental estimate for premature mortality related to short-term PM exposures is based on the pooled city-specific, short-term PM_{2.5} results from Schwartz, et al.

Based on advice from the SAB (EPA-SAB-Council-ADV-99-012, 1999), we examine ozone-related premature mortality as a supplemental estimate to avoid potential double-counting of benefits captured by the Pope, et al. PM premature mortality endpoint.^{hh} There are many studies of the relationship between ambient ozone levels and daily mortality levels. The supplemental estimate is calculated using results from only four U.S. studies (Ito and Thurston, 1996; Kinney et al., 1995; Moolgavkar et al., 1995; and Samet et al., 1997), based on the assumption that demographic and environmental conditions on average would be more similar between these studies and the conditions prevailing when the HD Engine/Diesel Fuel rule is implemented. However, the full body of peer-reviewed ozone mortality studies should be considered when evaluating the weight of evidence regarding the presence of an association between ambient ozone concentrations and premature mortality. We combined these studies using probabilistic sampling methods to estimate the impact of ozone on mortality incidence. The technical support document for this analysis provides additional details of this approach (Abt Associates, 2000). The estimated incidences of short-term premature mortality are valued using the value of statistical lives saved method, as described in Chapter VII.

The estimated effect of PM exposure on premature mortality in infants (post neo-natal) is based on a single U.S. study (Woodruff et al., 1997) which, on SAB advice, was deemed too uncertain to include in the primary analysis. Adding this endpoint to the primary benefits estimate would result in an increase in total benefits.

^{hh} While the growing body of epidemiological studies suggests that there may be a positive relationship between ozone and premature mortality, there is still substantial uncertainty about this relationship. Because the evidence linking premature mortality and particulate matter is currently stronger than the evidence linking premature mortality and ozone, it is important that models of the relationship between ozone and mortality include a measure of particulate matter as well. Because of the lack of monitoring data on fine particulates or its components, however, the measure of particulate matter used in most studies was generally either PM₁₀ or TSP or, in some cases, Black Smoke. If a component of PM, such as PM_{2.5} or sulfates, is more highly correlated with ozone than with PM or TSP, and if this component is also related to premature mortality, then the apparent ozone effects on mortality could be at least partially spurious. Even if there is a true relationship between ozone and premature mortality, after taking particulate matter into account, there would be a potential problem of double counting in this analysis if the ozone effects on premature mortality were added to the PM effects estimated by Pope et al., 1995, because, as noted above, the Pope, et al. study does not include ozone in its model.

As noted in Chapter VII, asthma affects over seven percent of the U.S. population. One study identifies a statistical association between air pollution and the development of asthma in some non-smoking adult men (McDonnell et al., 1998). Other studies identify a relationship between air quality and occurrences of acute asthma attacks or worsening of asthma symptoms. Supplemental estimates are provided for two asthma related endpoints. Occurrence of moderate or worse asthma symptoms in adults is estimated using a C-R function derived from Ostro, et al. (1991). Incidences of shortness of breath (in African American asthmaticsⁱⁱ) are estimated using a C-R function derived from Ostro, et al. (1995). The magnitude of these alternative calculations confirms the magnitude of the asthma attack endpoint estimated from the Whittemore and Korn (1980) study.

Occurrence of moderate or worse asthma symptoms are valued at \$41 per incidence (updated to 1999 dollars), based on the mean of average WTP estimates for the four severity definitions of a "bad asthma day," described in Rowe and Chestnut (1986), a study which surveyed asthmatics to estimate WTP for avoidance of a "bad asthma day," as defined by the subjects. Incidences of shortness of breath are valued at \$7 per incidence, based on the mean of the median estimates from three studies of WTP to avoid a day of shortness of breath (Ostro et al., 1995; Dickie et al., 1991; Loehman et al., 1979).

Table VII-A-1 presents estimated incidences and values for the supplemental endpoints listed above. The supplemental estimate of 1,200 avoided incidences of premature mortality from short-term exposures to PM indicates that these incidences are approximately 25 percent of the total premature mortality incidences estimated using the Pope, et al. study (4,300). This lends support for the assumption that 25 percent of the premature deaths predicted to be avoided in the first year using the Pope, et al. study should be assigned to the first year after a reduction in exposure.

The infant mortality estimate indicates that exclusion of this endpoint does not have a large impact, either in terms of incidences (13) or monetary value (approximately \$80 million). Estimates of the value for separate asthma endpoints are well under the estimate of the value of all respiratory symptoms. All of these supplemental estimates support the set of endpoints and assumptions chosen as the basis of the primary benefits estimate described in Chapter VII.

ⁱⁱShortness of breath due to PM exposure is not necessarily limited to African-American asthmatics. However, the Ostro et al. study was based on a sample of African-American children, who may be more sensitive to air pollution than the general population so we chose not to extrapolate the findings to the general population.

Table VII-A-1. Supplemental Benefit Estimates for the Final HD Engine/Diesel Fuel Rule for the 2030 Analysis Year^A

<i>Endpoint</i>	<i>Pollutant</i>	<i>Avoided Incidence^B (cases/year)</i>	<i>Monetary Benefits^C (millions 1999\$, adjusted for growth in real income)</i>
Premature mortality (short-term exposures) (all ages)	PM	2,600	\$19,230
Premature mortality (short-term exposures) (all ages)	Ozone	500	\$3,430
Premature mortality in infant population	PM	30	\$260
Any of 19 acute respiratory symptoms	PM and ozone	4,987,600	\$790
Shortness-of-breath (African-American asthmatics, 7-12)	PM	39,000	<\$1
Moderate or Worse Asthma (adult asthmatics, 18-65)	PM	182,500	\$10

^AOzone-related benefits estimated only for the Eastern U.S. due to ozone model performance issues (see chapter VII for details).

^B Incidences are rounded to the nearest 100.

^C Dollar values are rounded to the nearest 10.

C. Sensitivity Analyses

As discussed in Chapter VII, there are two key parameters of the benefits analysis for which there are no specific values recommended in the scientific literature. These parameters, the lag between changes in exposure to PM and reductions in premature mortality and the threshold in PM-related health effects, are investigated in this section through the use of sensitivity analyses. We perform an analysis of the sensitivity of benefits valuation to the lag structure by considering a range of assumptions about the timing of premature mortality. To examine the threshold parameter, we show how the estimated avoided incidences of PM-related premature mortality are distributed with respect to the level of modeled PM_{2.5}.

1. Alternative Lag Structures

As noted by the SAB (EPA-SAB-COUNCIL-ADV-00-001, 1999), “some of the mortality effects of cumulative exposures will occur over short periods of time in individuals with compromised health status, but other effects are likely to occur among individuals who, at baseline, have reasonably good health that will deteriorate because of continued exposure. No animal models have yet been developed to quantify these cumulative effects, nor are there epidemiologic studies bearing on this question.” However, they also note that “Although there is substantial evidence that a portion of the mortality effect of PM is manifest within a short period of time, i.e., less than one year, it can be argued that, if no a lag assumption is made, the entire mortality excess observed in the cohort studies will be analyzed as immediate effects, and this will result in an overestimate of the health benefits of improved air quality. Thus some time lag is appropriate for distributing the cumulative mortality effect of PM in the population.” In the primary analysis, based on SAB advice, we assume that mortality occurs over a five year period,

with 25 percent of the deaths occurring in the first year, 25 percent in the second year, and 16.7 percent in each of the third, fourth, and fifth years. Readers should note that the selection of a 5 year lag is not supported by any scientific literature on PM-related mortality. Rather it is intended to be a best guess at the appropriate distribution of avoided incidences of PM-related mortality.

Although the SAB recommended the five-year distributed lag be used for the primary analysis, the SAB has also recommended that alternative lag structures be explored as a sensitivity analysis (EPA-SAB-COUNCIL-ADV-00-001, 1999). Specifically, they recommended an analysis of 0, 8, and 15 year lags. The 0 year lag is representative of EPA's assumption in previous RIAs. The 8 and 15 year lags are based on the study periods from the Pope, et al. and Dockery, et al. studies, respectivelyⁱⁱ. However, neither the Pope, et al. or Dockery, et al. studies assumed any lag structure when estimating the relative risks from PM exposure. In fact, the Pope, et al. and Dockery, et al. studies do not contain any data either supporting or refuting the existence of a lag. Therefore, any lag structure applied to the avoided incidences estimated from either of these studies will be an assumed structure. The 8 and 15 year lags implicitly assume that all premature mortalities occur at the end of the study periods, i.e. at 8 and 15 years. We also present two additional lags: a 15 year distributed lag with the distribution skewed towards the early years and a 15 year distributed lag with the distribution skewed towards the later years. This is to demonstrate how sensitive the results are not only to the length of the lag, but also to the shape of the distribution of incidences over the lag period. It is important to keep in mind that changes in the lag assumptions do not change the total number of estimated deaths, but rather the timing of those deaths.

The estimated impacts of alternative lag structures on the monetary benefits associated with reductions in PM-related premature mortality (estimated with the Pope, et al. C-R function) are presented in Table VII-A-2. These estimates are based on the value of statistical lives saved approach, i.e. \$6 million per incidence, and are presented for both a 3 and 7 percent discount rate over the lag period. The results using the primary 5-year lag are repeated here for comparison. The table reveals that the length of the lag period is not as important as the distribution of incidences within the lag period. A 15-year distributed lag with most of the incidences occurring in the early years reduces monetary benefits less than an 8-year lag with all incidences occurring at the eighth year. Even with an extreme lag assumption of 15 years, benefits are reduced by less than half relative to the no lag and primary (5-year distributed lag) benefit estimates.

ⁱⁱAlthough these studies were conducted for 8 and 15 years, respectively, the choice of the duration of the study by the authors was not likely due to observations of a lag in effects, but is more likely due to the expense of conducting long-term exposure studies or the amount of satisfactory data that could be collected during this time period.

Table VII-A-2. Sensitivity Analysis of Alternative Lag Structures for PM-related Premature Mortality

Lag	Description	Monetary Benefit Adjusted for Growth in Real Income (millions 1999\$)		Percent of Primary Estimate	
		3% discount rate	7% discount rate	3% discount rate	7% discount rate
5-year distributed	Primary estimate, incidences are distributed with 25% in the 1 st and 2 nd years, and 16.7% in the remaining 3 years.	\$62,570	\$58,770	100%	94%
None	Incidences all occur in the first year	\$65,820	\$65,820	105%	105%
8-year	Incidences all occur in the 8 th year	\$53,520	\$40,990	86%	66%
15-year	Incidences all occur in the 15 th year	\$43,510	\$25,530	70%	41%
15-year distributed - skewed early	Incidences are distributed with 30% in the 1 st year, 25% in the 2 nd year, 15% in the 3 rd year, 6% in the 4 th year, 4% in the 5 th year, and the remainder 20% distributed over the last 10 years.	\$61,270	\$56,530	98%	90%
15-year distributed - skewed late	Incidences are distributed with 4% in the 11 th year, 6% in the 12 th year, 15% in the 13 th year, 25% in the 14 th year, and 30% in the 15 th year, with the remaining 20% distributed over the first 10 years.	\$47,200	\$31,280	75%	53%

2. PM Health Effect Threshold

The SAB advises that there is currently no scientific basis for selecting a threshold of 15 $\mu\text{g}/\text{m}^3$ or any other specific threshold for the PM related health effects considered in this analysis (EPA-SAB-Council-ADV-99-012, 1999). The most important health endpoint that would be impacted by a PM threshold is premature mortality, as measured by the ACS/Krewski, et al. (2000) C-R function. Krewski, et al. did not explicitly include a threshold in their analysis. However, if the true mortality C-R relationship has a threshold, then Krewski, et al.'s slope coefficient would likely have been underestimated for that portion of the C-R relationship above the threshold. This would likely lead to an underestimate of the incidences of avoided cases above any assumed threshold level. It is difficult to determine the size of the underestimate without data on a likely threshold and without re-analyzing the Krewski, et al. data. Nevertheless, it is illustrative to show at what threshold levels benefits are significantly affected.

Any of the PM-related health effects estimated in the primary analysis could have a threshold; however a threshold for PM-related mortality would have the greatest impact on the overall benefits analysis. Figure A-1 shows the effect of incorporating a range of possible thresholds, using 2030 PM levels and the ACS/Krewski, et al. (2000) study.

The distribution of premature mortality incidences in Figure A-1 indicate that approximately 90 percent of the premature mortality related benefits of the final HD Engine/Diesel Fuel rule are due to changes in PM concentrations occurring above 10 $\mu\text{g}/\text{m}^3$, and around 80 percent are due to changes above 12 $\mu\text{g}/\text{m}^3$, the lowest observed level in the ACS/Krewski, et al. study. Over 60 percent of avoided incidences are due to changes occurring above 15 $\mu\text{g}/\text{m}^3$.

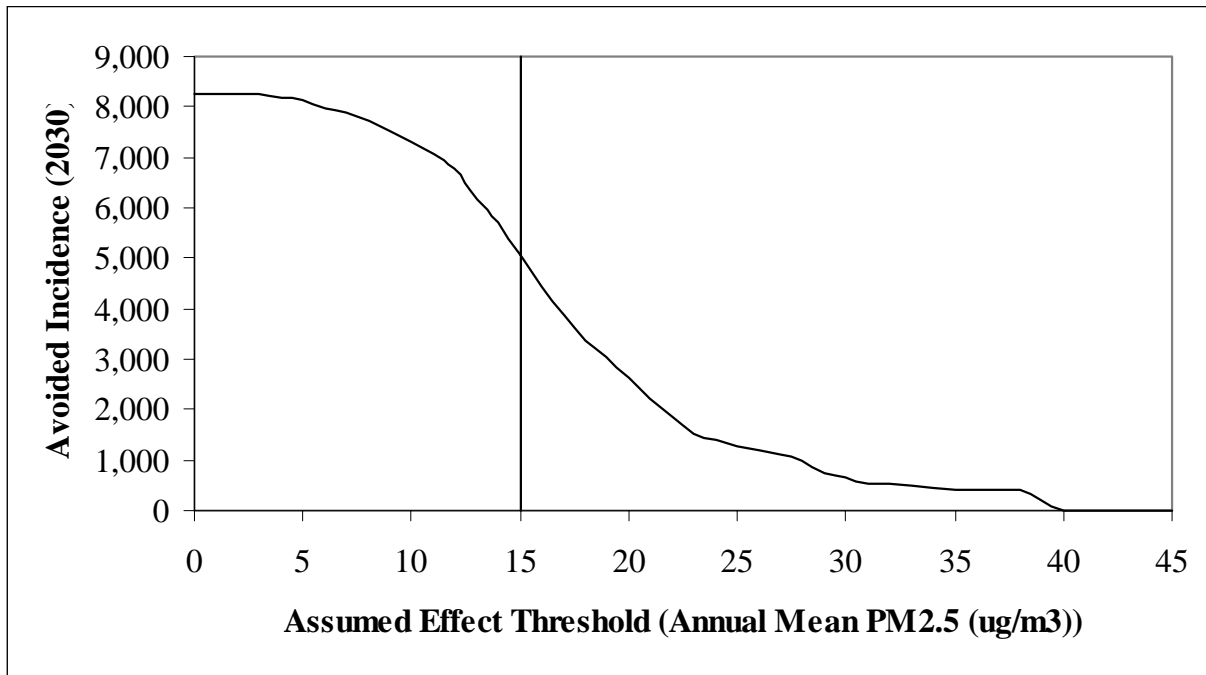


Figure VII-A-1. Impact of PM Health Effects Threshold on Avoided Incidences of Premature Mortality Estimated with the American Cancer Society/Krewski, et al. (2000) C-R Function

3. Income Elasticity of Willingness to Pay

As discussed in section C.1 of Chapter VII, our primary estimate of monetized benefits accounts for growth in real GDP per capita by adjusting the WTP for individual endpoints based on the primary estimate of the adjustment factor for each of the categories (minor health effects, severe and chronic health effects, premature mortality, and visibility). We examine how sensitive the primary estimate of total benefits is to alternative estimates of the income elasticities. The results of this sensitivity analysis are presented in Table VII-A-3. Note that the alternative elasticities and adjustment factors on which this sensitivity analysis is based are presented in Tables VII-11 and VII-12, respectively.

Consistent with the impact of mortality on total benefits, the adjustment factor for mortality has the largest impact on total benefits. The value of mortality ranges from 81 percent to 150 percent of the primary estimate based on the lower and upper sensitivity bounds on the income adjustment factor. The effect on the value of minor and chronic health effects is much less pronounced, ranging from 93 percent to 111 percent of the primary estimate for minor effects and from 88 percent to 110 percent for chronic effects.

Table VII-A-3. Sensitivity Analysis of Alternative Income Elasticities

Benefit Category	Lower Sensitivity Bound	Primary	Upper Sensitivity Bound
Minor Health Effect	\$510	\$550	\$610
Severe and Chronic Health Effects	\$2,120	\$2,420	\$2,670
Premature Mortality	\$50,680	\$62,580	\$94,140
Visibility ^A	—	\$3,260	—
Total Benefits	\$56,980	\$70,360	\$97,830

^A No range was applied for visibility because no ranges were available in the current published literature.

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Chapter VIII: Regulatory Flexibility Analysis

This chapter presents our Final Regulatory Flexibility Analysis (FRFA) which evaluates the impacts of the heavy-duty engine standards and diesel fuel sulfur standards on small businesses. Prior to issuing our proposal last June, we analyzed the potential impacts of our program on small businesses. As a part of this analysis, we convened a Small Business Advocacy Review (SBAR) Panel^a, as required under the Regulatory Flexibility Act as amended by the Small Business Regulatory Enforcement Fairness Act of 1996 (SBREFA). Through the Panel process, we gathered advice and recommendations from small entity representatives (SERs) who would be affected by the proposed engine and fuel standards. After the proposal was published in the Federal Register, we held five public hearings around the country to gather feedback on it. The small business provisions of today's action reflect revisions to the proposed program based upon updated analyses as well as comments heard at the public hearings and those submitted in writing during the public comment period.

A. Regulatory Flexibility Analysis

EPA has decided to prepare a Final Regulatory Flexibility Analysis (FRFA) for today's final rule. In accordance with section 603 of the RFA, EPA prepared an initial regulatory flexibility analysis (IRFA) for the proposed rule and convened a Small Business Advocacy Review Panel to obtain advice and recommendations of representatives of the regulated small entities in accordance with section 609(b) of the RFA (see 65 FR 35541, June 2, 2000). A detailed discussion of the Panel's advice and recommendations is found in the Panel Report contained in the docket for this rulemaking. A summary of the Panel's recommendations is presented at 65 FR 35541. The key elements of the FRFA include:

- the need for, and objectives of, the rule;
- the significant issues raised by public comments on the Initial RFA (IRFA), a summary of the Agency's assessment of those issues, and a statement of any changes made to the proposed rule as a result of those comments;
- the types and number of small entities to which the rule will apply;

^a Including representatives from the Small Business Administration, White House Office of Management and Budget, and EPA.

- the reporting, recordkeeping, and other compliance requirements of the rule, including the classes of small entities that will be affected and the type of professional skills necessary to prepare the report or record;
- the steps taken to minimize the significant impact on small entities consistent with the stated objectives of the applicable statute, including a statement of the factual, policy and legal reasons why the Agency selected the alternatives we did, and why other significant alternatives to the rule which affect the impact on small entities were rejected.

The RFA was amended by SBREFA to ensure that concerns regarding small entities are adequately considered during the development of new regulations that affect them. Although we are not required by the CAA to provide special treatment to small businesses, the RFA requires us to carefully consider the economic impacts that our rules will have on small entities. Specifically, the RFA requires us to determine, to the extent feasible, our rule's economic impact on small entities, explore regulatory options for reducing any significant economic impact on a substantial number of such entities, and explain our ultimate choice of regulatory approach.

In developing this rule, we concluded that the proposed heavy-duty engine and diesel fuel sulfur standards would likely have a significant impact on a substantial number of small entities. As discussed in more detail below, we identified several categories of small entities associated with diesel fuel production or distribution. To our knowledge, no manufacturers of heavy-duty engines meet the Small Business Administration (SBA) definition of a small business.

To comply with the requirements of the RFA, we quantified the economic impacts on the identified small entities. Using the methodology discussed in Chapter V, we determined the refinery costs for average size refineries and small refiners to produce low sulfur diesel fuel. Chapter V also contains our estimation of diesel distribution costs for the entire distribution system, including pipeline and tank wagon deliveries.

B. Need for and Objectives of the Rule

The preamble to this rule fully discusses the need for and objectives of this rule. As discussed in detail in Chapter II of this RIA, emissions from heavy-duty vehicles contribute greatly to a number of serious air pollution problems, and would have continued to do so into the future absent further controls to reduce these emissions. Although the air quality problems caused by diesel heavy-duty vehicles are challenging, we believe they can be resolved through the application of high-efficiency emissions control technologies. Based on the Clean Air Act requirements, we are setting stringent new emission standards that will result in the use of these diesel exhaust emission control devices. We are also finalizing changes to diesel fuel sulfur standards in order to enable these high-efficiency technologies. In consideration of the impacts that sulfur has on the efficiency, reliability, and fuel economy impact of diesel engine exhaust

emission control devices, we believe that controlling the sulfur content of highway diesel fuel to the 15 ppm level is necessary, feasible and cost effective. The standards will result in substantial benefits to public health and welfare and the environment through significant reductions in emissions of nitrogen oxides, particulate matter, nonmethane hydrocarbons, carbon monoxide, sulfur oxides, and air toxics.

C. Summary of Significant Public Comments on the IRFA

This FRFA addresses the issues raised by public comments on the IRFA, which was part of the proposal of this rule. EPA received many comments from small refiners and others pertaining to the options for hardship relief described in the NPRM. In general, many small refiners commented on the financial difficulty their refinery would face in complying with the proposed diesel sulfur program, and encouraged EPA to provide hardship relief. Many small refiners acknowledged that there was not one single hardship relief option to best suit the needs of all small refiners, and thus supported a menu of options. Section IV.C of the preamble discusses the three hardship relief options available to small refiners under today's program. These three options are based on concepts which were considered by the SBAR Panel and on which we requested and received comment in the proposal. A summary of the comments pertaining to regulatory alternatives for small refiners, and our response to them, is contained in the Response to Comments document contained in the docket.

D. Types and Number of Small Entities To Which The Rule Will Apply

Today's action will establish new heavy-duty engine standards and require low sulfur highway diesel fuel. It will primarily affect manufacturers of heavy-duty engines, petroleum refiners that produce diesel, and certain distributors of diesel fuel. As mentioned above, we are not aware of any heavy-duty engine manufacturers that would be defined as a small business under the SBA regulations (13 CFR Part 121). Although most refining companies are not considered small businesses, we have identified several refining companies that do appear to qualify under the applicable SBA definition. In addition, this rule may impact diesel fuel distributors and marketers—of which several thousand appear to be small businesses. Table VIII-1 below describes the affected industries, including the small business size standards SBA has established for each type of economic activity under the Standard Industrial Classification (SIC) and North American Industrial Classification (NAIC) systems. In this table, all the industry categories listed below the “Petroleum Refiners” category have some role in either distributing and/or marketing highway diesel fuel.

Table VIII-1. Industries Containing Small Businesses Potentially Affected by the Low Sulfur Diesel Fuel Rule

<i>Industry</i>	<i>NAICS^b Codes</i>	<i>SIC^c Codes</i>	<i>Defined by SBA as a Small Business if:^d</i>
Petroleum Refiners	324110	2911	≤1500 employees corporate-wide
Refined Petroleum Pipelines	486910	4613	≤1500 employees corporate-wide
Petroleum Marketers and Distributors	422710 422720	5171 5172	≤100 employees corporate-wide
Other Terminals: Special Warehousing and Storage	493110 493190	4226	≤\$18.5 million for the parent corporation
Fuel Oil Dealers	454311	5983	≤\$9 million for the parent corporation
Petroleum Retailers	447110 447190	5541	≤6.5 million for the parent corporation

The types and number of small entities to which the low sulfur diesel fuel rule will apply are described in Table VIII-2 below. Under this rule, the only small entities that may be significantly affected are small refiners, since they will have to invest in desulfurization technology to produce low sulfur highway diesel fuel. We estimate that small refiners produce approximately five percent of all highway diesel fuel in the U.S.

^b North American Industry Classification System

^c Standard Industrial Classification System

^d According to SBA's regulations (13 CFR 121), businesses with no more than the listed number of employees or dollars in annual receipts are considered "small entities" for purposes of a regulatory flexibility analysis.

Table VIII-2. Types and Number of Small Entities to Which the Diesel Sulfur Program Will Apply

<i>Type of Small Entity</i>	<i>Number of Companies Affected by the Low Sulfur Diesel Fuel Rule</i>
Small Refiners	Approximately 24
Small Diesel Marketers and Distributors	Several Thousand

1. Small Refiners

We have identified several refiners that produce highway diesel fuel and meet the SBA definition for a small petroleum refiner (Standard Industrial Classification (SIC) 2911), that is, having 1500 or fewer employees corporate-wide. These refiners, approximately 24 out of the approximately 124 refineries which produce highway diesel (there are about 158 refineries in the U.S. today), operate 27 refineries (i.e., some small refiners own and operate more than one refinery).

Some small refiners indicated that they will have greater difficulty than larger refiners in complying with the diesel sulfur standard due to such factors as limited operational flexibility, lack of access to alternate crude oil feedstocks, limited availability of new sulfur reduction equipment, poorer economies of scale, or difficulty in raising capital to finance projects. Based on these discussions and analyses, the Panel and we agree that small refiners would likely experience a significant and disproportionate financial hardship in reaching the objectives of our diesel fuel sulfur program. However, the Panel also noted that the burden imposed upon the small refiners by our sulfur requirements varied from refiner to refiner and could not be alleviated with a single provision. In addition, the small refiners strongly supported a “menu” of compliance options. We agree with the Panel and are offering qualifying small refiners three options to choose from in moving toward compliance with the low sulfur diesel fuel requirements.

2. Small Distributors/Marketers of Highway Diesel Fuel

The low sulfur diesel fuel rule contains certain downstream compliance and enforcement provisions, for all parties in the diesel fuel distribution system downstream of the refinery gate, to prevent 1) contamination of highway diesel fuels with fuels containing higher levels of sulfur and 2) misfueling of motor vehicles with high sulfur fuels.

Under this rule, distributors and retailers may choose to handle 500 ppm diesel fuel, 15 ppm diesel fuel, or both (as permitted under the temporary compliance option and small refiner hardship provisions described in the preamble). However, distributors and marketers will have to segregate low sulfur diesel fuel from other distillates just as they do today with 500 ppm diesel fuel. Retailers and wholesale purchaser-consumers will be responsible for ensuring that only low sulfur diesel fuel is sold for use in model year 2007 and later heavy-duty vehicles. Under the temporary compliance option and small refiner hardship provisions, where two grades of highway diesel fuel are allowed for the initial years of the program, some distributors and marketers may voluntarily decide (presumably based on economics) to add tankage or make additional modifications to accommodate two grades of highway diesel fuel. We have taken such costs into account in our diesel fuel cost analysis (described in more detail in Chapter V).

The low sulfur diesel fuel rule also includes a product downgrading restriction that is designed to discourage the intentional downgrading of 15 ppm diesel fuel to 500 ppm diesel fuel in the distribution system during the initial years of the program when the optional compliance provision is in effect. All parties in the distribution system downstream of the refinery gate are subject to this provision, except for those retailers that offer for sale and wholesale purchaser-consumers that use 15 ppm fuel either as the only grade of diesel or in addition to 500 ppm diesel (i.e., the only retailers and wholesale purchaser-consumers that are subject to this requirement are those that offer for sale or use only 500 ppm diesel but not 15 ppm diesel). Under this restriction, the volume of 15 ppm fuel that may be downgraded to 500 ppm highway diesel fuel at each point in the distribution system (downstream of the refinery gate) is limited to not more than 20 percent on an annual basis.^e Each party in the distribution system subject to this provision will be required to meet this requirement separately, based on the amount of 15 ppm fuel it receives and transfers/sells to the next party (or end user, in the case of retailers and wholesale purchaser-consumers) on an annual basis.

However, this provision should have no meaningful burden on downstream entities. It is only intended to prevent abuse and not intended to constrain any normal business operations. Furthermore, it does not require the addition of any new recordkeeping or reporting requirements beyond those required of the rest of the program.

E. Projected Costs of the Diesel Sulfur Standards

The average costs for a small refiner to produce low sulfur highway diesel fuel are described below:

^e The downgrading restriction applies only to 15 ppm downgraded to 500 ppm highway diesel fuel but not to 15 ppm downgraded to off-highway diesel fuel.

- A. capital cost: \$14 million
- operating cost: \$500 thousand per year
- per-gallon cost (assuming a seven percent ROI before taxes): 5.0 cents/gallon

In comparison, the average non-small refineries capital cost is \$52 million with operating costs of \$9.6 million per year. The per-gallon cost of average non-small refineries is 4.2 cents per treated diesel volume. Our methodology, including a comparison to recent industry estimates, is described in Chapter V.

As discussed in more detail in Chapter V.C., above, we also analyzed the increase in distribution costs associated with the low sulfur diesel fuel program. We estimate that distribution costs will increase by 0.5 cents per gallon of highway diesel fuel supplied when the sulfur requirements are fully effective beginning in the year 2010. During the initial years of the program, we estimate that there will be an increase in distribution costs of roughly \$1 billion for new storage tanks to handle two grades of highway diesel fuel (500 ppm and 15 ppm). The total distribution costs during the initial years of the low sulfur diesel fuel program equate to approximately 1.1 cents per gallon of the total volume of all highway diesel fuel supplied.

F. Projected Reporting, Recordkeeping, and Other Compliance Requirements of the Rule

The low sulfur diesel fuel program contains several hardship options to assist small refiners in producing low sulfur diesel fuel. Under these options, small refiners may be subject to new reporting and recordkeeping requirements to help ensure compliance with the options and the integrity of the low sulfur diesel fuel as it moves from the refinery gate to the retail outlet. However, we believe the benefits of the options will far outweigh any burdens imposed by their associated recordkeeping and reporting requirements.

The low sulfur diesel fuel program does not impose any new reporting requirements for small diesel marketers or distributors. However, this program does impose new record keeping requirements for such parties, specifically product transfer documents that track transfers of diesel fuel. Such transfer records are currently maintained by most parties for business and/or tax reasons. In addition, the record keeping requirements for downstream parties are fairly consistent with those in place today under other EPA fuel programs, including the current highway diesel fuel program. Therefore, we expect that the new record keeping requirements for downstream parties will not impose a significant burden.

1. Registration Reports

Refiners that are either currently producing or supplying highway diesel fuel, or that expect to do so by June 1, 2006, must register with us. The specific information required in the registration is described in section VII of the preamble as well as the regulations.

In addition to the basic registration requirements above, a refiner seeking status as a small refiner needs to apply for this status as a part of their registration and provide the average number of employees for all pay periods from January 1, 1999 to January 1, 2000, for the company, all parent companies, and all subsidiaries or joint ventures. The application also must include which small refiner option the refiner expects to use at each of its refineries.

2. Pre-Compliance Reports

All refiners (including small refiners) and importers must report to us regarding their progress toward compliance with the highway diesel fuel sulfur standards adopted today. These pre-compliance reports are due each May 31 from 2003 through 2005. We will maintain the confidentiality of information submitted in pre-compliance reports. We will present generalized data from the reports on a PADD basis in annual reports following the receipt of each year's pre-compliance reports. The specific information required in the compliance reports is described in Section VII of the preamble as well as the regulations.

In addition to the information required for all refiners, small refiners must provide additional information in their pre-compliance reports. The information required varies according to which small refiner option the refiner will be using, as discussed in Section IV.C of the preamble.

3. Annual Compliance Reports

After the highway diesel sulfur requirements begin June 1, 2006, refiners and importers will be required to submit annual compliance reports that demonstrate compliance with the requirements of this final rule. The first annual compliance report will be due by the end of February 2007 (for the period of June 1, 2006 through December 31, 2006) and would be required annually through February 2011. The specific information required in a refiner's annual compliance report is described in section VII of the preamble as well as the regulations. As with pre-compliance reports, in their annual compliance reports, small refiners must also supply additional information related to the small refiner option they are using.

4. Product Transfer Documents (PTDs)

In the low sulfur diesel fuel program, refiners as well as diesel distributors and marketers will be required to keep records primarily consisting of product transfer documents (PTDs), which document a party's diesel fuel transfers. Such records are already maintained by most parties for business or tax purposes. We are adopting the proposed requirements that refiners, importers, distributors, and marketers provide information on commercial PTDs that identifies diesel fuel distributed for use in motor vehicles and states that the fuel is compliant with the 15 ppm sulfur standard. Since the low sulfur diesel fuel rule adopts provisions for the production and sale of 500 ppm sulfur diesel fuel for use in pre-2007 model year vehicles, the rule also adopts provisions which require PTDs to identify such fuel and state that its use in motor vehicles is restricted to pre-2007 motor vehicles.^f We believe this additional information on commercial PTDs is necessary to 1) prevent the commingling of highway diesel fuel with high sulfur distillate products, 2) avoid contamination of 15 ppm highway diesel fuel with 500 ppm highway diesel fuel, and 3) prevent the misfueling of model year 2007 and later vehicles with any fuel having a sulfur content greater than 15 ppm. To discourage the intentional downgrading of 15 ppm diesel fuel to 500 ppm diesel fuel in the distribution system during the initial years of the program, PTDs must also include the volume of each fuel grade (15 ppm and 500 ppm) delivered.^g

5. Recordkeeping Requirements

Refiners that produce (or importers that import) both 500 ppm highway diesel fuel and 15 ppm highway diesel fuel under the temporary compliance option or any hardship program (including small refiners), or that produce only 15 ppm sulfur content diesel fuel and that wish to generate credits (including early credits), must maintain records for each batch of highway diesel fuel produced, of the batch designations and the batch volumes. The refiner must maintain records regarding credit generation, use, transfer, purchase, or termination. The specific recordkeeping information required under the low sulfur diesel fuel program is described in section VII of the preamble as well as the regulations.

Small refiners approved for temporary hardship relief due to extreme unforeseen circumstances or extreme financial hardship must include certain information in their application for relief. The required information, and the factors we will consider in determining what relief, if any, is appropriate, are discussed in Section IV.B.3 of the preamble. Such refiners will also

^f Such fuel can also be used in nonroad vehicles, whose fuel is currently unregulated.

^g As discussed in Section VII of the preamble, we are restricting the volume of 15 ppm fuel that can be downgraded to 500 ppm highway diesel fuel at each point in the distribution system to not more than 20 percent on an annual basis.

have reasonable recordkeeping and reporting requirements, which will be determined on a case-by-case basis.

6. Diesel Fuel Pump Labeling

The low sulfur diesel fuel rule also adopts pump labeling requirements for retailers and wholesale purchaser-consumers similar to the requirements that we proposed, but with modifications to account for the availability of diesel fuel subject to the 500 ppm sulfur standard for use in pre-2007 motor vehicles. For any multiple-fuel program, like the low sulfur diesel fuel program with its compliance flexibility option and hardship provisions, clearly labeling diesel fuel pumps is vital for end users to distinguish between the two grades of fuel. We received comments on the proposal that concurred with our assessment that pump labels, in conjunction with vehicle labels, would help to prevent misfueling of motor vehicles with high sulfur diesel fuel. The text of the labels appears in Section VII of the preamble; the specific requirements for label size and appearance are found in the regulatory language for this rule.

G. Regulatory Alternatives

For today's action, we have structured a selection of temporary flexibilities for qualifying small refiners, both domestic and foreign, based on the factors described below. Generally, we structured these provisions to address small refiner hardship while expeditiously achieving air quality benefits and ensuring that the low sulfur diesel fuel coincides with the introduction of 2007 model year diesel vehicles. First, the compliance deadlines in the program, combined with flexibility for small refiners, will quickly achieve the air quality benefits of the program, while helping to ensure that small refiners will have adequate time to raise capital for new or revamped equipment. Second, we believe that allowing time for refinery sulfur-reduction technologies to be proven out by larger refiners before small refiners have to put them in place will likely allow for lower costs of these improvements in desulfurization technology (e.g., better catalyst technology or lower-pressure hydrotreater technology). Third, providing small refiners more time to comply will increase the availability of engineering and construction resources. Since most large and small refiners must install additional processing equipment to meet the sulfur requirements, there will be a tremendous amount of competition for technology services, engineering manpower, and construction management and labor. Finally, because the gasoline and diesel sulfur requirements will occur in approximately the same time frame, small refiners that produce both fuels will have a greater difficulty than most other refiners in securing the necessary financing. Hence, any effort that increases small refiners' ability to stagger investments for low sulfur gasoline and diesel will facilitate compliance with the two programs. These factors are discussed further in Section IV.C of the preamble.

Providing these options to assist small refiners experiencing hardship circumstances enables us to go forward with the 15 ppm sulfur standard beginning in 2006. Without this

flexibility, the benefits of the 15 ppm standard would possibly not be achieved as quickly. By providing temporary relief to those refiners that need additional time, we are able to adopt a program that expeditiously reduces diesel sulfur levels in a feasible manner for the industry as a whole. In addition, we believe the volume of diesel that will be affected by this hardship provision is marginal. We estimate that small refiners contribute approximately five percent of all domestic highway diesel fuel production.

All refiners producing highway diesel fuel are able to take advantage of the temporary compliance option discussed in Section IV.A of the preamble. Refiners that seek and are granted small refiner status may choose from the following three options under the diesel sulfur program. These three options have evolved from concepts on which we requested and received comment in the proposal. In most cases, we believe that small refiners will find these options preferable to either the broader diesel fuel temporary compliance option or the Geographic Phase-in Area (GPA) provisions (as applicable) discussed in the preamble.

500 ppm Option. A small refiner may continue to produce and sell diesel fuel meeting the current 500 ppm sulfur standard for four additional years, through May 31, 2010, provided that it reasonably assures the existence of sufficient volumes of 15 ppm fuel in the marketing area(s) that it serves.

Small Refiner Credit Option. A small refiner that chooses to produce 15 ppm fuel prior to 2010 may generate and sell credits to other refiners under the broader diesel temporary compliance option. Since a small refiner has no requirement to produce 15 ppm fuel under this option, any volume of fuel it produced at or below 15 ppm sulfur will qualify for generating credits.

Diesel/Gasoline Compliance Date Option. For small refiners that are also subject to the Tier 2/Gasoline sulfur program (40 CFR Part 80), the refiner may choose to extend by three years the duration of its applicable interim gasoline standards, provided that it also produces all its highway diesel fuel at 15 ppm sulfur beginning June 1, 2006.

1. 500 ppm Option

The 500 ppm Option is available for any refiner that qualifies as a small refiner. Under this option, small refiners could continue selling highway diesel fuel with sulfur levels meeting the current 500 ppm standard for four additional years, provided that they supply information showing that sufficient alternate sources of 15 ppm diesel fuel in their market area will exist for fueling new heavy-duty highway vehicles. Under this option, small refiners could supply current 500 ppm highway diesel fuel to any markets for use only in vehicles with older (pre-2007) technology through May 31, 2010. In other words, small refiners that choose this option may delay production of highway diesel fuel meeting the 15 ppm standard for four years.

This 500 ppm option for small refiners is similar to the option provided to all refiners in the temporary compliance option described in Section IV.A of the preamble in that it allows a refiner to continue to produce and sell current 500 ppm fuel for a period of time. However, this option differs from the broader temporary compliance option in that small refiners could produce and sell 100 percent of their highway fuel at 500 ppm without needing to buy credits. By way of contrast, under the broader program, refiners would need to buy credits in order to produce any volume of 500 ppm fuel over 20 percent of their total highway diesel production.

2. Small Refiner Credit Option

We believe that the relative difficulty for small refiners to comply with today's program warrants compliance flexibility for these refiners. At the same time, we want to encourage all refiners to produce 15 ppm sulfur as early and in as many geographic areas as possible. As an incentive for small refiners to invest in desulfurization capacity, those that choose to produce 15 ppm fuel earlier than they would need to under the 500 ppm option—before 2010—could generate credits for each gallon of diesel fuel produced as meeting the 15 ppm standard. They could then sell these credits to other refiners for use in the broader diesel fuel program described above in Section IV.A, helping to offset some of the cost of producing the cleaner fuel.

Under this option, credits could be generated based on the volume of any diesel fuel meeting the 15 ppm standard. The refiner could sell its remaining highway diesel fuel under the 500 ppm option above.

3. Diesel/Gasoline Compliance Date Option

The Tier 2/Gasoline Sulfur program included a special provision that applies for refiners that qualify as small refiners (40 CFR Part 80, Subpart H). Under that program, each small refiner is assigned an interim gasoline sulfur standard for each of its refineries. This interim standard for each refinery is established based on the baseline sulfur level of that refinery. The standards are designed to require each small refiner to either make a partial reduction in their gasoline sulfur levels or, if they already produce low sulfur fuel, to maintain their current levels. The gasoline interim program lasts for four years, 2004 through 2007, and the refiner can apply for an extension of up to two years. After the interim program expires, small refiners need to produce the same low sulfur gasoline as other refiners.

Today's diesel sulfur program takes effect in the same time frame as the small refiner interim program for gasoline sulfur. To avoid the need for simultaneous investments in both gasoline and diesel fuel desulfurization, several small refiners subject to both programs raised the concept of allowing those investments to be staggered in time. Because of the relative difficulty small refiners will face in financing desulfurization projects, especially for both diesel and gasoline desulfurization in the same time frame, we agree that this concept has merit and have

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adopted it for this rule. Under this concept, small refiners could extend the duration of their gasoline sulfur interim standards and, thus, potentially postpone some or all of their gasoline desulfurization investments while they work to achieve the diesel sulfur standards “on time” in 2006. To the extent that small refiners choose this Diesel/Gasoline Compliance Date option, this provision will benefit the overall diesel program because it will increase the availability of 15 ppm diesel fuel in the small refiner’s market area.

Specifically, this option provides that a small refiner can receive a three-year extension of a refinery’s interim gasoline standard, until January 1, 2011, if it meets two criteria: 1) it produces both gasoline and diesel fuel at a refinery and chooses to comply with the 15 ppm diesel fuel sulfur standard by June 1, 2006 for all its highway diesel production at that same refinery, and 2) it produces a minimum volume of 15 ppm fuel at that refinery that is at least 85 percent of the average volume of highway diesel fuel that it produced at that refinery during calendar years 1998 and 1999. We believe that it is very important that the extension of a small refiner’s interim low sulfur gasoline standard be linked to a substantial environmental benefit from the production of low sulfur diesel fuel in 2006. We have established a minimum volume requirement to prevent the Diesel/Gasoline Compliance Date option from applying in situations where a refiner changes its refinery product slate to produce very little highway diesel fuel—even though this production is at a 15 ppm sulfur level—and yet receives an extension of its interim gasoline sulfur standard. We believe the 85 percent level is sufficient to reflect a substantial investment in desulfurization technology. At the same time the 85 percent level should allow for any reasonable variation in production of highway diesel fuel that would be expected to occur in typical situations between now and 2006, particularly given the continued growth of the highway diesel market. Again, the three-year extension of the gasoline interim program is to allow small refiners to stretch out their capital investments while increasing the quantity of 15 ppm fuel being produced. We expect that small refiners using this option will make a substantive capital investment in diesel desulfurization and have thus set this minimum 15 ppm diesel volume limit.

The Tier 2/Gasoline Sulfur program includes a general hardship provision for which refiners may apply. (Today’s program also includes a similar provision). Depending on the nature of its hardship, a small refiner that applies for this general hardship provision under the gasoline program could be granted a “tailor-made” interim gasoline sulfur program different from the “default” program established in the rule. If such a small refiner were then to be covered by today’s diesel fuel requirements and chose this Diesel/Gasoline Compliance Date option, we would allow it an extension of its special interim program for gasoline (as established under the general hardship provision) for three years beyond the scheduled end date (although no later than December 31, 2010) so long as it met the 15 ppm diesel fuel standard in 2006.

4. Relationship of the Options to Each Other

By definition, since a small refiner must produce 100 percent of its highway diesel as 15 ppm under the Diesel/Gasoline Compliance Date option, that option is not compatible with either the 500 ppm option or the Small Refiner Credit option. Thus a refiner choosing the Diesel/Gasoline Compliance Date option may not choose either of the other two options. However, the 500 ppm option and the Small Refiner Credit option are compatible with each other, and so a refiner can choose either or both of these options.

H. Other Relevant Federal Rules Which May Duplicate, Overlap, or Conflict with the Low Sulfur Diesel Fuel Rule

The heavy-duty engine and diesel fuel sulfur standards that we are finalizing are similar, in many respects, to existing regulations; in some cases, these regulations are replacing earlier requirements with more stringent requirements for refiners and engine manufacturers. We also note that more stringent diesel sulfur standards will likely require many refiners to obtain permits from state and local air pollution control agencies under the CAA's New Source Review program prior to constructing the desulfurization equipment needed to meet the standards. However, we are not aware of any area where the new regulations will directly duplicate or conflict with existing federal, state, or local regulations.

On the other hand, several small refiners commented that the low sulfur diesel fuel program overlaps with the low sulfur gasoline program. Specifically, they indicated that they will be making substantial investments to comply with the low sulfur gasoline program (which phases in from January 1, 2004 through December 31, 2007) while concurrently planning and investing to comply with the low sulfur diesel fuel program. One hardship option within the low sulfur diesel fuel program was specifically designed for those small refiners that produce both gasoline and highway diesel fuel. The intent of this option, which is described in more detail below, is to help small refiners spread out their gasoline and diesel fuel desulfurization investments.

Chapter IX: Sulfur Control in Alaska & Territories

A. What is the Authority For Exemptions?

Section 211(c) of the Clean Air Act allows EPA to regulate fuels where emission products of the fuel either: 1) cause or contribute to air pollution that reasonably may be anticipated to endanger public health or welfare, or 2) will impair to a significant degree the performance of any emission control device or system which is in general use, or which the Administrator finds has been developed to a point where in a reasonable time it would be in general use were such a regulation to be promulgated. EPA's authority to establish emissions standards for heavy-duty engines and vehicles is based on section 202(a)(3), directing EPA to establish regulations under section 202(a) that produce the greatest achievable reductions, considering various factors such as technological feasibility, cost, and lead-time. Under section 211(c), EPA is required to consider available scientific and economic data, including a cost benefit analysis comparing emission control devices or systems which are or will be in general use and require the control or prohibition with emission control devices or systems which are or will be in general use and do not require the control or prohibition.

Sections 211(i) and 211(g) of the Clean Air Act restrict the use of high-sulfur diesel fuel in highway vehicles. Section 211(i)(1) prohibits the manufacture, sale, supply, offering for sale or supply, dispensing, transport, or introduction into commerce of motor vehicle (highway) diesel fuel which contains a concentration of sulfur in excess of 0.05 percent by weight (500 ppm), or which fails to meet a minimum cetane index of 40, beginning October 1, 1993. Section 211(i)(2) required EPA to promulgate regulations to implement and enforce the requirements of paragraph (1), and authorized EPA to require that diesel fuel not intended for highway vehicles be dyed in order to segregate that fuel from highway vehicle diesel fuel. Section 211(i)(4) provides that the states of Alaska and Hawaii may seek an exemption from the requirements of subsection 211(i) in the same manner as provided in section 325^a of the Act. Section 211(g)(2) of the Act prohibits the fueling of highway vehicles with diesel fuel containing sulfur in excess of 500 ppm or which fails to meet a cetane index of 40 beginning October 1, 1993.

^a Section 211(i)(4) mistakenly refers to exemptions under Section 324 of the Act ("Vapor Recovery for Small Business Marketers of Petroleum Products"). The proper reference is to section 325, and Congress clearly intended to refer to section 325, as shown by the language used in section 211(i)(4), and the United States Code citation used in section 806 of the Clean Air Act Amendments of 1990, Public Law No. 101-549. Section 806 of the Amendments, which added paragraph (i) to section 211 of the Act, used 42 U.S.C. 7625-1 as the United States Code designation, the proper designation for section 325 of the Act. Also see 136 Cong. Rec. S17236 (daily ed. October 26, 1990) (statement of Sen. Murkowski).

Section 325 of the Act provides that upon the request of Guam, American Samoa, the Virgin Islands, or the Commonwealth of the Northern Mariana Islands, EPA may exempt any person or source, or class of persons or sources, in that territory from any requirement of the Clean Air Act, with some specific exceptions. The requested exemption could be granted if EPA determines that compliance with such requirement is not feasible or is unreasonable due to unique geographical, meteorological, or economic factors of the territory, or other local factors as EPA considers significant.

The EPA highway vehicle diesel fuel regulation at 40 CFR 80.29 implements the sulfur and cetane requirements of section 211(i) of the Clean Air Act. In addition, that regulation establishes the requirement to dye diesel fuel that is not intended for highway vehicles. It specifies that any diesel fuel that does not show visible evidence of the dye solvent red 164 is considered to be available for use in highway vehicles and subject to the sulfur and cetane index requirements.

B. Alaska Exemption From the 500 ppm Sulfur Standard

1. Why Are We Considering an Exemption for Alaska?

On February 12, 1993, Alaska submitted a petition^b under section 325 of the CAA to exempt highway vehicle diesel fuel in Alaska from paragraphs (1) and (2) of section 211(i) of the CAA, except for the minimum cetane index requirement. The petition requested that we temporarily exempt highway vehicle diesel fuel in communities served by the Federal Aid Highway System from meeting the sulfur content (500 ppm) specified in section 211(i) of the CAA and the dye requirement for non-highway diesel fuel of 40 CFR 80.29, until October 1, 1996. The petition also requested a permanent exemption from those requirements for areas of Alaska not reachable by the Federal Aid Highway System -- the remote areas. On March 22, 1994, (59 FR 13610), we granted the petition based on geographical, meteorological, air quality, and economic factors unique to Alaska.

On December 12, 1995 Alaska, submitted a petition for a permanent exemption for all areas of the state served by the Federal Aid Highway System, that is, those areas covered only by the temporary exemption. On August 19, 1996, we extended the temporary exemption until October 1, 1998 (61 FR 42812), to give us time to consider comments to that petition that were subsequently submitted by stakeholders. On April 28, 1998 (63 FR 23241) we proposed to grant

^b Copies of information regarding Alaska's petition for exemption and subsequent requests by Alaska and actions by EPA are available for inspection in public docket A-96-26 at the Air Docket of the EPA, first floor, Waterside Mall, room M-1500, 401 M Street SW., Washington, D.C. 20460. A duplicate public docket is at EPA Alaska Operations Office-Anchorage, Federal Building, Room 537, 222 W. Seventh Avenue, #19, Anchorage, AK 99513-7588.

the petition for permanent exemption. Substantial public comments and substantive new information were submitted in response to the proposal. To give us time to consider those comments and new information, we extended the temporary exemption for another nine months until July 1, 1999 (September 16, 1998, 63 FR 49459). During this time period, we started work on a nationwide rule to consider more stringent diesel fuel requirements, particularly for the sulfur content (today's action). To coordinate the decision on Alaska's request for a permanent exemption with the new nationwide rule on diesel fuel quality, we extended the temporary exemption until January 1, 2004 (June 25, 1999 64 FR 34126).

In today's final rule, we are extending the temporary exemption from the 500 ppm sulfur standard to the effective date for the new nationwide 15 ppm sulfur standard in 2006. While it is important to implement in Alaska the cleaner diesel engines and fuel of the final rule, our goal is to take action on the petition in a way that minimizes costs through Alaska's transition to the new low sulfur program. The cost of compliance could be reduced if Alaska refiners were given the flexibility to meet the low sulfur standard in one step (i.e., going straight from uncontrolled levels to the new 15 ppm standard in 2006), rather than in two steps (i.e., going from uncontrolled levels to the current 500 ppm standard in 2004, and then to the new 15 ppm standard in 2006). We considered the prior public comments we received as a result of our previous notices and actions regarding exemptions from the 500 ppm sulfur standard for highway diesel fuel in Alaska.

2. Who Commented on the 1998 Proposal for a Permanent Exemption?

Comments in support of the permanent exemption from the current 500 ppm sulfur standard were submitted by the Alaska Department of Environmental Conservation, a fuel producer association (Alaska Oil and Gas Association), individual fuel producers (MAPCO, Alaska Petroleum, Petro Star, Arco Alaska, and BP Exploration), fuel distributors (Yutana Barge Lines, Kodiak Oil Sales, and Petro Marine Services), a trade association (Resource Development Council of Alaska), a utility association (Alaska Rural Cooperative Association), and some individual businesses including the Anchorage International Airport and Alaska Railroad Corporation.

Comments opposed to the permanent exemption from the current 500 ppm sulfur standard were submitted by the Trustees for Alaska (Trustees) and individuals. Represented by the Trustees, besides themselves, are the Cook Inlet Keeper, the Oregon Chapter Sierra Club, the Alaska Chapter Sierra Club, the Alaska Clean Air Coalition including the Alaska Center for the Environment, the American Lung Association of Alaska, the Alaska Health Project, the Anchorage Audubon Society, and the League of Women Voters of Anchorage. Their comments generally related to Alaska's geography, meteorology, economics and health and welfare. The

specific comments submitted by individuals generally were the same as some of the specific comments submitted by the Trustees.

Comments opposed to the permanent exemption from the current 500 ppm sulfur standard were also submitted by the Engine Manufacturers Association (EMA). Its comments related to engine manufacturer warranty and recall liability, and the impact of operating advanced technology engines on Alaska's high-sulfur diesel fuel.

3. What are the Relevant Factors Unique to Alaska?

It should be noted that while the following section discusses factors unique to Alaska in the context of the current 500 ppm sulfur standard (vis-a-vis the exemption), in general we believe these factors are relevant to the new 15 ppm sulfur standard as well.

a. Geography, meteorology, and fuel production, distribution, usage

Alaska is about one-fifth as large as the combined area of the lower 48-states. Because of its extreme northern location, rugged terrain and sparse population, Alaska relies on barges to deliver a large percentage of its petroleum products. No other state relies on this type of delivery system to the extent Alaska does. Only 35 percent of Alaska's communities are served by the Federal Aid Highway System, which is a combination of road and marine highways. Approximately 19 percent of these communities (approximately 18 communities) are part of the Alaska Marine Highway System and have heavy-duty diesel vehicles registered with the Alaska Division of Motor Vehicles and rely on barge deliveries.^c The remaining 65 percent of Alaska's communities are referred to as "off-highway" or "remote" communities, which are all served by barge lines. Although barge lines can directly access some off-highway communities, those communities that are not located on a navigable waterway are served by a two-stage delivery system: over water by barge line and then over land to reach the community.

Ice formation on the navigable waters during the winter months restricts fuel delivery to the areas served by barge lines. Therefore, fuel is generally only delivered to these areas between the months of May and October. For example, Kodiak Oil commented to the 1998 proposal that during the winter of 1989, Cook Inlet (inlet to Anchorage) froze and "we were down to our last gallons when a barge arrived from Seattle. We even had to borrow jet fuel from the U.S. Coast Guard to use as heating oil." This distribution problem also restricts the ability of fuel distributors in Alaska to supply multiple grades of petroleum products to these communities.

^c Letter from Alaska Department of Environmental Conservation to EPA dated August 11, 1998.

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The Alaska Department of Environmental Conservation reported construction costs are 30 percent higher in Alaska than in the lower-48 states.^d This increase is due to higher freight costs for materials, and higher electrical, mechanical and civil costs due mostly to higher labor costs. Also, because of the State's high latitude, it experiences seasonal extremes in the amount of daily sunlight and temperature, which in turn affects the period of time during which construction can occur.

According to Alaska's petition, its extreme northern location places it in a unique position to fuel transcontinental cargo flights between Europe, Asia, and North America. Roughly 75 percent of all air transit freight between Europe and Asia lands in Anchorage, as does that between Asia and the United States. The result is a large market for jet fuel (Jet-A kerosene) produced by local refiners, which decreases the relative importance of highway diesel fuel to these refiners. Based on State tax revenue receipts and estimates by Alaska's refiners, diesel fuel consumption for highway use represents roughly five percent of total Alaska distillate fuel consumption.^e The Trustees commented in 1998 that, according to 1996 and 1997 information from the Alaska Department of Revenue, highway diesel actually represents between 11 percent and 13 percent of the distillate market. We could not confirm the Trustees' figures. Using the tax data submitted in Appendix A^f of the Trustees comments to the 1998 proposal, we calculated that Alaska used 5.9 percent and 6.3 percent of its total distillate consumption for motor vehicles for the fiscal years ending June 30, 1996, and June 30, 1997, respectively.^g Using that same data, the Alaska Department of Environmental Conservation reported to us that it derived "approximately 5 percent" for these same years.^h In that same submittal, the Alaska Department

^d IBID.

^e EPA independently verified the distillate consumption estimates based on statistics from the Federal Highway Administration and the Department of Energy. These statistics show that in 1997 the proportion of jet fuel consumption compared to total distillate consumption was approximately 66 percent for Alaska, compared to approximately 27 percent for the United States. The proportion of diesel fuel consumption for highway use compared to total distillate consumption was approximately 5 percent for Alaska, compared to approximately 30 percent for the United States.

^f Attachment A from the comments submitted by the Trustees in response to the 1998 proposal included state tax revenue data from the Alaska Internet site at <http://www.revenue.state.ak.us/iea/>. Attachment A includes Table 9 - Taxable Motor Fuel Gallons Sold in Alaska for the fiscal year ending June 30, 1996, and Table 6 - Taxable Fuel Gallons Sold in Alaska for the fiscal year ending June 30, 1997.

^g These ratios were derived by dividing the adjusted diesel used for highway purposes by the total distillate. The adjusted diesel usage was calculated by subtracting all non-highway usage from the reported "gross gallons sold" of highway diesel. The fuel subtracted included "exemptions" for fuel used for heating, exported, off-highway, utilities, power plants, and drilling well injection. The total distillate was calculated as the sum of the gross "highway" diesel, Jet fuel, and marine diesel.

^h Letter from ADEC to EPA dated August 11, 1998.

of Environmental Conservation also reported that industry calculations based on the same data source show 4.2 percent for 1996. We note that the above calculations ranging from 4.2 percent to 7 percent agree reasonably well with the original estimate of 5 percent.

Alaska's highway diesel vehicle fleet is relatively small, particularly outside the Federal Aid Highway System, and these vehicles are predominantly older than the national average. There are less than 9000 diesel vehicles in Alaska, with less than 600 of these vehicles in all of rural Alaska. By comparison, there are about 7.2 million diesel vehicles in the entire nation. Thus, the Alaska diesel fleet represents only about 1/800 of the national diesel fleet. These vehicles are also older on average. The average age of the diesel fleet in the areas served by the Federal Aide Highway System is about 14 years, and the average age of the vehicles in the rural areas is about 18 years. Only about 200 to 400 new model year diesel vehicles are added to the state's diesel fleet each year, and only about 5 to 15 in the state's rural areas. By comparison, the average age of the national diesel fleet is about 10 years, and about 300,000 to 500,000 new model year diesel vehicles are added to the national diesel fleet each year.ⁱ

Information provided to us by the State of Alaska indicates that refiners supply and distribute conventional diesel fuel in the summer which has a sulfur content of approximately 3000 ppm, and supply and distribute Jet-A kerosene in the winter as an Arctic-grade diesel, which has a sulfur content between 650 and 1100 ppm from Alaskan refiners, and 300 ppm from one refiner in the lower-48 states. Where the Jet-A kerosene is used as conventional diesel fuel and not for aviation, it is generally mixed in the same tanks with conventional diesel fuel. The fuel type supplied and delivered is based strictly on economics, availability, and whether winter grade fuel is needed. Where some or all of the Jet-A kerosene is used as aviation fuel, it must be segregated from conventional diesel fuel to avoid contamination. Aviation fuel must meet stringent specifications, and contamination would disqualify the fuel as aviation fuel. The same barge and truck tankers and transfer equipment apparently can deliver both types of fuel without significant contamination of the Jet-A kerosene. However, dyed non-highway diesel fuel is a serious concern. According to the refiners and distributors in Alaska, if Alaska were required to dye its non-highway diesel fuel, residual dye in tanks or transfer equipment would be enough to contaminate and disqualify Jet-A kerosene for use as aviation fuel. Either the tanks and transfer equipment would have to be thoroughly cleaned prior to handling jet fuel, or separate tankage and transfer equipment would be needed.

Alaska's climate is colder than that of the other 49 states. The extremely low temperatures experienced in a large portion of Alaska during the winter imposes a more severe fuel specification requirement for diesel fuel in those parts of Alaska than in the rest of the

ⁱ We compared diesel vehicle registration data (12,000 pound and greater, unladen weight) as of October 1998 provided by the state of Alaska to national diesel vehicle data as described by the input data to the EPA MOBILE model for the 1999 calendar year.

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country. This specification, known as a "cloud point" specification^j significantly affects vehicle start-up and other engine operations. Alaska has the most severe cloud point specification for diesel fuel in the nation at -56°F. Because Alaska experiences extremely low temperatures in comparison to the other 49 states, and the cloud point specifications for diesel fuel in the other 49 states are not as severe, most diesel fuel used in Alaska is produced by refiners located in Alaska. Jet-A kerosene meets the same cloud point specification as No. 1 diesel fuel (which is marketed primarily during the winter in Alaska, as opposed to No. 2 diesel fuel which is marketed primarily in the summer) and is commonly mixed with or used as a substitute for No. 1 diesel fuel. However, Jet-A kerosene can have a sulfur content as high as 3000 ppm. The current highway diesel fuel sulfur standard of 500 ppm, and the new sulfur standard of 15 ppm, would prohibit using Jet-A kerosene from being used as a fuel for motor vehicles, unless the sulfur content of the Jet-A kerosene were also reduced to meet these standards.

The Trustees, in their 1998 comments, challenged past statements by refiners and the State regarding the technical feasibility of meeting the 500 ppm sulfur standard in Alaska compared to the lower-48 states. The Trustees indicated that while Alaska's climate may be colder on a state-by-state basis, Alaska's climatic conditions are not unique relative to other states when considered on a city-by-city basis. The Trustees noted that we have not granted cities in the lower-48 states exemptions from the low sulfur diesel regulations. The Trustees also commented that in light of Canada's implementation of 500 ppm sulfur diesel fuel regulations, we should examine the methods used by cities and towns located in northern Canada, including the Yukon and the Northwest Territories, to overcome cloud point difficulties. We believe that Alaska is technically capable of complying with the current 500 ppm sulfur standard (as well as the new 15 ppm sulfur standard), but that cost is the primary issue.

In complying with the 500 ppm (or the new 15 ppm) sulfur standard, refiners have the option to invest in the process modifications necessary to desulfurize diesel fuel for use in motor vehicles, or not invest in the process modifications and either import low sulfur diesel fuel from outside of Alaska or only supply diesel fuel for non-highway purposes (e.g., heating, generation of electricity, nonroad vehicles). Previously, most of Alaska's refiners indicated that local

^j The cloud point defines the temperature at which cloud or haze or wax crystals appears in the fuel. The purpose of the cloud point specification is to ensure a minimum temperature above which fuel lines and other engine parts are not plugged by solids that form in the fuel. This specification is designated by the American Society for Testing and Materials (ASTM) in its "Standard Specification for D975-96 Diesel Fuel Oils", and varies by area of the country and by month of the year based on historical temperature records. Alaska has the most stringent cloud point specification in the United States. For example in January, Alaska's cloud point specification is -56°F, -26°F, and -2°F for the northern (above 62° latitude), southern (below 62° latitude), and Aleutian Islands plus southeastern coast region, respectively. In contrast, the most stringent cloud point specification in January in the lower-48 states is -29°F for Minnesota. For the state of Washington, from which some distillate is imported into Alaska, the January cloud point specification is +19.4°F and 0°F for the western and eastern parts of the state, respectively.

refineries would choose to exit the market for highway diesel fuel if an exemption from the 500 ppm sulfur requirement is not granted. They pointed to their limited refining capabilities, the small size of the market for highway diesel fuel in Alaska, and the costs that would be incurred to desulfurize diesel fuel (to meet the 500 ppm standard). Among the reasons for the high cost include the construction costs in Alaska, which are 25 to 65 percent higher than costs in the lower-48 states, and the cost of modifying the fuel production process itself.

The 1998 proposal indicated that the Alaskan refineries cannot produce 500 ppm diesel fuel without significant capital expenditures for desulfurization equipment and operation. In response to that proposal, MAPCO (now Williams Energy Services) commented the installation of the necessary equipment at MAPCO's North Pole refinery would cost over \$100 million for a diesel hydrotreater, a hydrogen plant, a sulfur recovery unit, additional tankage and associated piping, utilities, etc. MAPCO indicated this cost estimate does not include needed new tankage at MAPI's Anchorage Terminal "where MAPI has found it almost impossible to build additional tankage to build adequate additional tankage because of difficulties in obtaining the required permits". Further, MAPCO indicated the refinery would have to dispose of waste sulfur material in a landfill, likely in an out-of-state disposal site at additional cost for disposal. MAPCO explained that local borough landfills are nearing capacity and struggling with identifying long term options, and that other borough landfill sites are not likely to accept waste generated outside their own borough. MAPCO further commented that all non-taxable non-highway diesel fuel would have to be dyed (the current temporary exemption also exempts the dye requirement). For MAPI alone, this would mean dyeing over 100 million gallons of diesel per year at a cost of over \$125,000 per year for blending infrastructure, cost of dye, management of dyeing operation, maintenance, laboratory, QA, accounting and loading personnel. Similarly, the Alaskan Oil and Gas Association (AOGA) commented the total cost to retrofit Alaskan refineries (for 500 ppm sulfur diesel fuel) has been estimated to be "in excess of \$150 million." Tesoro indicated that it is currently producing 500 ppm diesel fuel at a cost of about four to six cents per gallon using low sulfur crude product, but would likely need desulfurization equipment to reach the new sulfur limit of 15 ppm.

In its 1998 comments, the Trustees noted that in March of 1998, Petro Star, Inc. signed a commercial license agreement with Energy Biosystems Corporation for a biocatalytic desulfurization unit, the costs of which are significantly less than the current hydro-treating method. They noted that after we granted the "urban" exemption, Tesoro announced plans to spend \$50 million in 1997 to "beef up" its Nikiski refinery (near Anchorage on Kenai Peninsula), expand its network of Alaska gas stations and renovate existing stores, and to spend an additional \$30 million over 1998-99 for further store expansion and renovations. They noted that the State of Alaska's Industrial Development and Export Authority later announced it would help finance \$8.1 million of the cost of Tesoro's refinery improvements. They further noted that MAPCO also was in the midst of a \$11 million refinery expansion in 1997. The Trustees commented that EPA

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should, therefore, ignore complaints by local refineries that the cost of retrofitting are too much for them to bear in order to supply Alaskans with cleaner fuel.

It appears there are two related cost issues that need to be addressed. One is whether refiners can afford the retrofits to produce highway diesel fuel that meets the 500 ppm (and the new 15 ppm) sulfur standard. Their 1998 comments seem to have focused not on whether the refiners can afford the retrofits, but on cost benefits: the anticipated high costs of 500 ppm diesel fuel and the lack of significant environmental benefits for Alaska. According to the Alaska Department of Environmental Conservation, MAPCO's and Tesoro's expansions "were built because they are profitable investments. This is unlike the capital cost required for 500 ppm diesel. One refiner indicated that they do not see this as a profitable investment, but a burden to consumers, refiners, and fuel distributors in Alaska."^k However, we have indications that Alaska's refiners may now be considering options for sulfur control.

The second related issue is the cost of producing 500 ppm (or 15 ppm) diesel fuel. Our analysis of the costs to meet the 15 ppm sulfur standard, described in Chapter V, are significantly lower than that indicated by MAPCO (now Williams) to meet the 500 ppm standard. Further, the costs of desulfurization may prove to be less than estimates using the standard hydrogenation process if new technologies as discussed in Chapter IV become prove to be commercially viable.

The 1998 proposal discussed Alaska's potential ability to import diesel fuel from the lower-48 states. In that proposal, we explained that the fuel currently being imported into Southeast Alaska either does not meet the federal sulfur standard (500 ppm) for motor vehicles, or is not arctic grade, or both, thus the cost of requiring 500 ppm diesel fuel would likely increase. The Trustees subsequently commented that there are many northern cities and towns in the lower-48 states that need 500 ppm diesel fuel with a low cloud point, and that we failed to explain where those northern cities and towns obtain their low sulfur, low cloud point diesel fuel, or the inability of the lower-48 state refineries to provide Alaska with 500 ppm diesel fuel. Based on available information, we believe lower-48 state refineries are probably capable of producing and marketing 500 ppm (and 15 ppm) arctic grade diesel fuel for Alaska, but there are likely cost implications for producing that fuel in the lower-48 states and in transporting it to Alaska.

The Trustees commented in 1998 that based on information provided in the 1998 proposal, the price of imported fuel is not overly expensive or unreasonable. In response to this comment, we looked at the price of diesel fuel in the lower-48 states, and the cost to distribute fuel to Alaska from the lower-48 states. Two sources of distillate prices indicate the average price difference between high sulfur and 500 ppm diesel fuel in the lower-48 states is about 2.1

^k IBID.

to 2.5 cents per gallon.¹ MAPCO submitted an invoice for one vessel shipment of 42,779.20 barrels (1,796,726 gallons) of gasoline from Puget Sound to Anchorage at a cost of \$300,000, or 16.7 cents per gallon. We assume that the cost to ship diesel fuel depends on the distance the fuel is shipped, and that it is similar to the cost of shipping gasoline. Adding this shipping cost (16.7 cents per gallon) to the average price difference between high sulfur and 500 ppm sulfur diesel fuel in the lower-48 states (2.1 to 2.5 cents per gallon), the estimated direct cost of replacing locally produced high sulfur highway diesel fuel in Anchorage with imported 500 ppm diesel fuel from the lower-48 states could be 18.8 to 19.2 cents per gallon.

This cost estimate does not consider any additional cost that may be associated with producing special batches of 500 ppm diesel fuel having a low cloud point specification in the lower-48 states. EPA has no estimates of such cost, but at least two factors must be considered. First, it is likely that low-cloud point specification fuel costs more to produce because of its special formulation, and the fact that it is produced only to the extent it is specifically requested by purchasers. Second, the demand for low-cloud point specification fuel for Alaska would not likely coincide in time with the demand for low cloud point specification fuel in the lower-48 states. Alaska distributes and stocks its winter fuel during the summer and fall months, when summer fuel is being produced and delivered in the lower-48 states. For example, the Colonial Pipeline requests winter grade fuel beginning in September, so that it will be available for use in the Northeast states by about the end of October.^m Thus, refiners in the lower-48 states would just be gearing up to produce winter fuel for the lower-48 states when they would be gearing down production of winter fuel for Alaska. Those refiners would have to produce special batches of fuel destined for Alaska in the spring and summer months, and refiners and distributors in the lower-48 states would have to store and transport this fuel while keeping it segregated from other diesel fuel destined for use in the lower-48 states and from any other high-sulfur diesel fuel destined for use in Alaska.

The Trustees also commented in 1998 that we should provide evidence that transportation costs would increase. In the 1998 proposal, we concluded that increased transportation costs would be either zero or minimal for Southeast Alaska because most if not all its fuel is already imported to that area. However, the shipping costs would increase for other areas which currently obtain their fuel from in-state refineries, and that increase would likely be "more than minimal." Comments to that proposal submitted by MAPCO (Docket A-96-26, IV-D-6) indicated our information was dated, and that much of the diesel fuel in Southeast Alaska now

¹ According to the DOE "Monthly & Annual Petroleum Supply Data" for 1997, the average price of 500 ppm #2 diesel fuel in the United States in 1997 was 2.1 cents per gallon more than the average price of high-sulfur #2 diesel. Also, according to Hart's Diesel Fuel News for January through March of 2000, 500 ppm distillate averaged 2.5 cents per gallon more than low sulfur distillate for New York, Houston and Chicago.

^m Electronic mail to EPA staff by the American Petroleum Institute on October 12, 1998.

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comes from in-state refiners. Regardless, we consider the cost of transporting fuel produced in the lower-48 states to Alaska is the sum of the cost of transporting the fuel in the lower-48 states (e.g., from the refinery to Seattle) and the cost of transporting the fuel to Alaska from the lower-48 states (e.g., from Seattle to Anchorage). The transportation cost within the lower-48 states, for which we do not have a cost estimate, is incurred regardless of whether the fuel produced in the lower-48 states is destined for use in the lower-48 states or Alaska. Thus, the transportation cost within the lower-48 states should already be incorporated into the cost of fuel being sold in the lower-48 states. An example of transportation cost from the lower-48 states to Alaska was provided by MAPCO, which submitted an invoice for one vessel shipment of 42,779.20 barrels (1,796,726 gallons) of gasoline from Puget Sound to Anchorage at a cost of \$300,000, or 16.7 cents per gallon.

We stated in the 1998 proposal that Canadian 500 ppm diesel fuel does not seem to be available for export to Alaska. The Trustees commented in 1998 that this conclusion was based on 1995 information, that Canada recently passed regulations requiring all on-road vehicles to use 500 ppm diesel fuel, and Canadian refineries may now welcome the opportunity to supply Alaska with 500 ppm diesel. In response to this comment, EPA contacted Transport Canada, which indicated Western Canada has greater ability to produce 500 ppm products than other areas of Canada, but that some Western Canadian refiners have indicated that they do not have enough capacity to supply 500 ppm diesel fuel with a -57° F cloud point to Alaska. The cloud point limit requires the fuel to be made from the same streams used to make Jet-A kerosene, and "there is simply not enough of this material available in Western Canada to supply Alaska, in addition to meeting domestic Jet A-1 and northern diesel demands." But even if some Canadian refiners could supply 500 ppm diesel fuel to Alaska, "[t]he costs for distribution would be significant."ⁿ In addition, Canada's highway diesel fuel would not meet the requirements of today's rule (15 ppm sulfur), unless Canada subsequently would adopt these new requirements for Canada. Canada has recently publically announced its intention to adopt a highway diesel sulfur standard consistent with our final rule.^o

Cost is relevant not only for the likely higher cost of replacement of imported fuel (due to importation costs, decreased competition, etc.), but for total impact on the Alaskan economy. For example, in response to the 1998 proposal, the Anchorage International Airport (Airport) commented that increased costs of highway diesel fuel could significantly impact Alaskans through increased capital and operating costs for airports, tenants, as well as other Alaskan industries and businesses relying on diesel fuel. It said these increased costs would be passed on to end-users. The Airport also indicated many small businesses are relied on in Alaska due to the

ⁿ Information submitted to EPA on July 20, 1998 by Transport Canada via electronic mail

^o "Process Begins to Develop Long Term Agenda to Reduce Air Pollution from Vehicles and Fuels", Environment Canada press release, May 26, 2000

state's expansive size, undeveloped transportation system, and rural markets. It said that these added capital and operating costs combined with logistical difficulties would place many small but needed businesses common at airports and throughout Alaska at a great disadvantage. The Alaska Railroad Corporation commented that although railroads would not be required to use 500 ppm highway diesel, it anticipates a reduction in the quantity of petroleum products it transports from the MAPCO refinery in Fairbanks for use throughout Alaska. It said some of its diesel fuel business would be diverted to out-of-state refiners, reducing railroad revenues, thereby increasing the cost of transporting other goods and services, and thus causing customers to evaluate other less fuel-efficient alternatives.

Whether 500 ppm (or 15 ppm) diesel fuel is produced in Alaska or imported from the lower-48 states or Canada, there remains the problem of segregating the two fuels for transport to communities that are accessible only by navigable waterways and subsequent storage of the fuels in those communities. Fuel is delivered to these communities only between the months of May and October due to ice formation which blocks waterways leading to these communities for much of the remainder of the year. The fuel supplied to these communities during the summer months must last through the winter and spring months until resupply can occur. Additionally, the existing fuel storage facilities limit the number of fuel types that can be stored for use in these communities. The cost of constructing separate storage facilities and providing separate tanks for transport of 500 ppm diesel fuel for motor vehicles could be significant. This is largely due to the high cost of construction in Alaska relative to the lower 48 states, and the constraints inherent in distributing fuel in Alaska.

One alternative to constructing separate storage facilities is to supply only 500 ppm diesel fuel to these communities. However, this would require use of the higher cost, 500 ppm diesel fuel for all diesel fuel needs. This would increase the already high cost of living in these communities, since a large percentage of distillate consumption in these communities is for non-highway uses, such as operating diesel powered electrical generators. The Trustees commented in 1998 that we offered little evidence that 500 ppm diesel fuel would cost more, and in fact, 500 ppm diesel fuel may be less expensive. In our 1998 proposal, we indicated that "the distributors import the more expensive Jet-A kerosene for all uses because limited storage prevents segregation among the intended uses." Where segregation is not possible, we believe the distributors have to supply fuel that meets the most stringent requirements among the various uses of the fuel. Presently, the most stringent requirements are for jet fuel. As long as fuel is needed for aviation purposes and can not be segregated from the fuel used for other purposes, all fuel has to meet the more stringent and more costly jet fuel specifications. Similarly, if 500 ppm diesel fuel were required for highway use and segregation were not possible, all fuel would have to meet both the more costly jet fuel specifications and the more costly 500 ppm motor vehicle diesel fuel specification. Our cost estimates for refiners to desulfurize to the new 15 ppm sulfur standard are discussed in Chapter V.

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Also, Alaska would not be able to avoid segregating the fuel simply by supplying only 500 ppm diesel fuel for all uses. If the EPA 500 ppm sulfur content exemption were to expire or be terminated, the automatic Internal Revenue Service (IRS) exemption for Alaska would also expire, and the IRS would require that the non-highway fuel (except jet fuel) be segregated and dyed. The IRS tax code has a diesel fuel dye requirement that parallels that of the EPA, but areas of Alaska covered by an EPA diesel sulfur exemption are also exempt from the IRS dye requirement (26 CFR 48.4082-5T). Consequently, if the EPA exemption were to expire or be terminated and fuel producers and distributors decided to supply only 500 ppm diesel fuel for economic or other reasons, the producers and distributors would still have to dye and segregate the non-highway fuel (except jet fuel) for federal tax purposes or pay the highway fuel tax. The jet fuel intended for aviation would have to be segregated from jet fuel intended for general usage to avoid being contaminated with the dye.

In response to the 1998 proposal, we received significant comments from industry and businesses in Alaska on the issue of storage and segregation. We listed the most significant of these comments below. Note that while these issues were raised in response to the exemption decision for the current 500 ppm standard, they are generally relevant to the new 15 ppm sulfur standard as well.

The Anchorage International Airport commented that construction of separate storage and distribution facilities will be at "substantial capital and operating costs."

Kodiak Oil commented that there is not a lot of use of diesel fuel by vehicles. Diesel fuel is used for other purposes, including fishing boats, ocean transportation (tug boats), heating oil, off-road construction equipment, off-road logging and fish processing. Currently there is no need to segregate the fuel by use. The costs associated with 500 ppm diesel would be borne by a small segment of the market and would require a large expense in new tanks and pipelines for a small part of sales. Kodiak Oil further stated that fuel distributors can't send tank trucks to a fuel terminal in another town to load it up and drive it back. They must receive fuel by barge in large volumes and must have a large investment in tanks and equipment to store it.

Petro Marine Services commented that the vast majority of its product is used by vessels, and very little of it is sold to motor vehicles. If it were required to segregate 500 ppm diesel for use by motor vehicles, separate tanks would be required for distribution and storage, which would represent a huge cost for a very small volume of fuel.

Petro Star commented that segregated storage would be required to distribute 500 ppm diesel in many areas, and such storage would be unfeasible or prohibitively expensive.

ARCO commented the demand for motor vehicle fuel is small compared to other uses of its "Arctic Heating Fuel" (similar to No. 1 diesel fuel produced by ARCO Alaska Inc. for use in

exploration and production in the North Slope) and it would be very expensive to construct separate storage tanks for a second type of diesel fuel.

The Alaska Oil and Gas Association commented that because 500 ppm diesel must be segregated from non-road diesel, separate distribution, storage and delivery systems must be installed. It estimates that there are approximately 80 tank farms located throughout Alaska, many of them in remote areas. Without the exemption all of these locations would be required to construct and maintain separate facilities.

Yutana Barge Lines, Inc. commented that over 95 percent of the diesel that Yutana Barge Lines, Inc. hauls is either for marine or power generation. It calculated the cost to be approximately 18 cents per gallon to properly segregate the dyed and undyed fuel, and build the additional facilities and equipment to ship and store the dyed and undyed fuel.

MAPCO (now Williams Energy Services) commented that additional tankage and segregation of piping systems in the Alaska distribution system could easily cost \$50 million, assuming that permits can be obtained. There is a shortage of tankage for storage and distribution of products throughout the state. As a result, in Anchorage MAPCO ships and stores imported ethanol (for oxygenated gasoline during the control period for CO) in rail cars at a cost of over 27 cents per gallon. MAPCO has tried to build new tanks to expand its storage and distribution capabilities, but has been unable to obtain the associated air permits. It indicated similar permitting and storage challenges exist throughout the state. There are over 80 tank farms in Alaska that would require additional tankage. These tank farms are widely dispersed and delivery times are such that considerable storage volume would have to be dedicated to 500 ppm diesel. The cost of constructing one 10,000 barrel tank with all required spill containment and supporting infrastructure is at least \$600,000. MAPCO also commented that segregated tanker trucks would be required to haul the dyed fuels in order to avoid cross contamination with other non-dyed diesel and jet kerosene. The cost for each additional truck is approximately \$250,000. Contamination of other fuels by the dye (dyeing non-highway fuel, except jet fuel, would be required without the exemption) is a serious potential problem. Jet fuel is quite easily stained by the dye and in Alaska many of the same trucks that haul the heating fuel also haul the highway diesel and jet fuel.

The Trustees commented in 1998 that we should clarify why distributors are presently capable of segregating summer and winter fuels, but if the exemption were denied, distributors would not be capable of segregation. In response, it is likely that distributors are presently capable of segregating the currently available fuels, but not additional fuels. For example, where only Jet-A kerosene is currently used for all purposes (under the current sulfur and dye exemptions), no segregation may presently be needed. Where both Jet-A kerosene and conventional diesel fuel are currently available (under the current sulfur and dye exemptions), adequate segregated storage may presently exist for the Jet-A kerosene (for jet use and all other

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uses in the winter) and conventional diesel fuel (including a mixture of conventional diesel and Jet-A kerosene) in the summer. In each case, if we do not extend the sulfur and dye exemptions beyond January 1, 2004, additional tankage would likely be required to segregate the 500 ppm highway diesel fuel, and additional tankage may be required to segregate jet fuel intended for aviation purposes from the jet fuel intended for other non-highway uses, which would have to be dyed in accordance with the EPA and IRS requirements.

The Trustees commented in 1998 that studies by members of the diesel engine manufacturing and petroleum refining industries prompted by the 1990 diesel rule (55 FR 34121, August 21, 1990) found that the potential cost benefit to truck owners and operators of using 500 ppm diesel fuel compared to conventional diesel fuel is between 8 and 30 cents per gallon, and this benefit would more than offset any cost increase incurred in requiring the use of 500 ppm diesel. Actually, in promulgating the 500 ppm requirement in 1990, we estimated cost savings to truck owners and operators from sulfur control to range from 0.8 to 30 cents per gallon, depending on the method used to evaluate the benefits and the vehicle class evaluated. While we have not gone back to reevaluate the benefits of the 500 ppm sulfur cap, we do believe the use of the new 15 ppm fuel in upcoming engine technologies is very likely to offer benefits in addition to those resulting from the 500 ppm cap (see chapters III and V). More importantly, as discussed in chapter III, we believe that the use of diesel fuel with sulfur levels greater than the 15 ppm sulfur limit will not be viable with the use of the engine technologies necessary to meet the new 2007 vehicle emission standards.

b. Environmental and Health Factors

Since Alaska has been operating under diesel sulfur exemptions since 1993, continuing the diesel sulfur exemption would not cause emissions to significantly increase, but would mean Alaska would forego the potential benefits to its air quality resulting from the use of 500 ppm diesel fuel. The only violations of national ambient air quality standards in Alaska have been for carbon monoxide (CO) and particulate matter (PM₁₀). CO violations have been recorded in the State's two largest communities: Anchorage and Fairbanks. PM₁₀ violations have been recorded in two rural communities, Mendenhall Valley of Juneau and Eagle River in Anchorage. The most recent PM₁₀ inventories for these two communities, although more than a decade old, show that these violations are largely the result of fugitive dust from paved and unpaved roads, and that diesel motor vehicles are responsible for less than one percent of the overall PM₁₀ being emitted within the borders of each of these areas^p. Moreover, Eagle River has not had a violation of the PM₁₀ standard since 1986. Mendenhall Valley has initiated efforts for road paving to be implemented to control road dust. The sulfur content of highway diesel fuel will not likely have a significant impact on ambient PM₁₀ or CO levels in any of these areas because of the minimal

^p "PM₁₀ Emission Inventories for the Mendenhall Valley and Eagle River Areas," prepared for the U.S. Environmental Protection Agency, Region X, by Engineering-Science, February 1988.

contribution by diesel motor vehicles to PM₁₀ in these areas and the insignificant effect of diesel fuel sulfur content on CO emissions.

The use of high-sulfur (>500 ppm) diesel fuel may cause plugging or increased particulate sulfate emissions in diesel vehicles equipped with trap systems or oxidation catalysts, and could impair the ability of oxidation catalysts to reduce hydrocarbons (HC) and CO exhaust emissions. However, any increase in sulfate particulate emissions would likely have only a minor effect on ambient PM₁₀ levels in Alaska since current diesel motor vehicle contributions to PM₁₀ emissions are minimal.

The Trustees asserted in their comments to the 1998 proposal that given half of Alaska's highway fuel consumption is diesel, diesel particles can be expected to be significant contributors to wintertime air pollution. They also claim the State of Alaska bases an assertion that diesel vehicles are negligible contributors to the ambient PM₁₀ problems on inaccurate data. Alaska calculated that by using 500 ppm diesel fuel the maximum reduction in PM₁₀ emissions would be 70 tons per year. Alaska based this figure on the assumption that the annual highway diesel fuel consumption is 50 million gallons. According to the Trustees, recent records show Alaskans consume closer to 200 million gallons of highway diesel fuel each year. They concluded that if Alaska used 500 ppm diesel fuel, the State would reduce its PM₁₀ emissions by 280 tons per year instead of the 70 tons estimated by the State. The Trustees indicated this reduction, whether significant in proportion to other PM₁₀ sources, is in the best interests of the health and well-being of Alaskan residents. The Trustees also commented they are concerned about inventory numbers during wintertime air pollution events in Anchorage and Fairbanks. They claimed Alaska has evidence that Anchorage and Fairbanks events are mostly vehicular pollution with measurable amounts of woodsmoke and that fine particle pollution is present during wintertime inversions that result in high pollution levels.

Any reduction of particulate emissions is likely to be beneficial to health at some level. However, we could not substantiate that half of Alaska's highway fuel consumption is diesel fuel. Compared to the total highway consumption of gasoline and diesel fuel combined, the diesel fuel highway consumption is approximately 24 percent, based on Alaska revenue data for the fiscal year ending 1997 submitted by the Trustees in Attachment A to their comments to the 1998 proposal. That same revenue data indicate that highway vehicles in Alaska consume about 80 million gallons of diesel fuel annually. Using these statistics, the reduction in PM₁₀ by using 500 ppm diesel fuel for highway vehicles would be about 112 tons per year.

The Trustees noted in their 1998 comments that in 1994, engine manufacturers began designing their engines with catalysts to meet the 1994 emission standards with the use of 500 ppm diesel fuel. They further concluded that when a diesel engine equipped with a catalyst burns high-sulfur diesel fuel, sulfate emissions increase. Alaska had argued that because of the small size of the new (1994 and later) vehicle fleet on Alaskan roads, the increase in sulfate emissions

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would be insignificant. The Trustees noted that at the time the Petition was submitted in 1995, Alaska's assertion may have been true, but as each year passes, more and more diesel engines equipped with catalysts join the Alaska fleet. The Trustees commented that EPA should examine the effect that increased numbers of diesel vehicles with catalysts have on emissions inventories.

Based on available information and analysis, increased sulfate emissions with the use of high-sulfur (>500 ppm) diesel fuel and oxidation catalyst technology is a possibility. However, with few exceptions, engine manufacturers are now complying with our current emission standards without the use of oxidation catalysts. Therefore, the concern is unlikely to grow.

The Trustees commented in 1998 that we should consider the impact of the new national ambient air quality standard (NAAQS) for particulate matter (PM_{2.5}) that we recently promulgated. However, as we stated in the 1998 proposal, it is untimely to consider the impact of the new NAAQS for PM_{2.5}. We may revisit this issue again in the future if and when actions on the NAAQS revisions are complete. Following a NAAQS revision, state Governors must submit recommendations for designations. These are designations of “nonattainment,” “attainment,” and “unclassifiable.” Under section 6102(c)(1) and 6102(d) of the Transportation Equity Act for the 21st Century (TEA-21) concerning the designation process for a PM_{2.5} NAAQS, we will not make designations for PM_{2.5} until after at least three calendar years of air quality data have been gathered, which have been measured by Federal reference method monitors, or equivalent monitors. We anticipate that three years of quality assured data will be available from the first set of PM_{2.5} monitors by 2002, and from all of the monitors by 2003. Under section 6102(c)(1) of the TEA-21, states will be required to submit designations referred to in section 107(d)(1) of the Clean Air Act for each area concerning PM_{2.5} within one year after receipt of three years of quality assured air quality data from Federal reference method monitors or equivalent monitors. Under section 6102(d) of the TEA-21, we would then have to promulgate designations referred to in section 106(d)(1) of the Clean Air Act for a PM_{2.5} NAAQS by the earlier of one year after the date States are required to make their submittal or by December 31, 2005. Consequently, data indicating whether Alaska is complying with a new PM_{2.5} NAAQS would not be available until at least 2002 or 2003, and the compliance designation for Alaska would not be promulgated until at least 2004 or 2005. Nevertheless, based on very limited information available at this time, there is no substantive indication that Alaska would be in noncompliance with a PM_{2.5} NAAQS, or that requiring 500 ppm (or 15 ppm) diesel fuel for motor vehicles in Alaska would significantly impact Alaska's prospects for attainment with a PM_{2.5} NAAQS.

The Trustees commented in 1998 that emissions monitoring results submitted in support of Alaska's petition do not provide a reliable basis for judging the potential adverse health effects of continuing the Alaska exemption in perpetuity. They explained that in Anchorage, for example, the Alaska Department of Environmental Conservation has two fixed monitoring sites for PM₁₀ and one fixed monitoring site for PM_{2.5}. The Trustees noted that neither Alaska's

petition nor our 1998 proposal indicate whether these sites are located in areas of high diesel use, and commented that the Alaska Department of Environmental Conservation must accurately monitor diesel emissions in representative locations if we intend to rely on such data in making its decision. In response to this comment, the Alaska Department of Environmental Conservation submitted a letter to us that includes technical detail regarding the monitoring sites.⁹

The Trustees commented in 1998 that, while we, and the state of Alaska, may be correct in our assertion that sulfur content in motor vehicle diesel fuel will not significantly affect ambient PM₁₀ problems in Alaska, we failed to consider that Congress enacted the 500 ppm requirement for additional reasons, especially because of sulfur effects on human health. The Trustees stated that Congress passed Section 211(i) of the Clean Air Act because it was concerned about particulates which cause cancer, genetic mutation and other health related ailments. There is a discussion of the legal requirements for today's action in the Appendix.

The Trustees commented in 1998 that Alaska provides a brief and wholly inadequate analysis of problems caused by high-sulfur content (> 500 ppm) diesel fuel and then summarily concludes that Alaskan residents will not experience any health problems should we chose to grant the exemption to the 500 ppm standard. The Trustees asserted that a complete analysis of health effects caused by exposure to diesel exhaust must be included in our final decision to grant or deny Alaska's petition. The Trustees further asserted that we must recognize and discuss the fact that sulfur causes health problems in two primary ways from Alaskan residents. First, inhalation of sulfur or sulfur dioxide (SO₂) causes health problems. Second, high sulfur content diesel fuels increase diesel exhaust which in turn causes an increase in emission of all major criteria air pollutants in exhaust, including carbon monoxide, hydrocarbons, and nitrogen oxides.

We are concerned about the emissions and health impact of sulfur in diesel fuel, as discussed at length in Chapter II. This discussion is prefaced by the presumption that implementing the new 15 ppm fuel standard in Alaska, along with the new diesel motor vehicle engine and diesel motor vehicle emission standards, is expected to eventually reduce emissions from diesel motor vehicles in Alaska from current levels (assuming diesel vehicle miles traveled in Alaska do not significantly increase). If the new fuel standard is not implemented in Alaska, those emission reduction benefits will not be achieved, and some increased emissions would result from the use of high sulfur (> 15 ppm) fuel in upcoming engine and vehicle technologies. In fact, as discussed in chapter III, the upcoming engine and vehicle technologies would not be feasible on diesel fuel having a sulfur content greater than 15 ppm.

⁹ Letter of August 11, 1998 from the Alaska Department of Environmental Conservation. Copies of that letter are in the EPA Public Docket A-96-26 located in Washington D.C. and in Anchorage, Alaska.

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The Trustees commented in 1998 that granting a fuel exemption for Alaska's mobile sources prevents the development of 500 ppm diesel supply sources in Alaska that can be economically tapped by stationary sources and off-highway engines. The Trustees indicated that according to the Alaska Department of Environmental Conservation, almost all villages in Alaska depend on diesel generators to produce power for utility purposes. Most of these diesel generators are located in close proximity to residences and community centers, such as schools, where the exposure to diesel fumes is most problematic. The Trustees commented that these communities would benefit by the availability of 500 ppm diesel fuel.

We agree that there could be secondary air quality benefits to requiring 500 ppm (or 15 ppm) diesel fuel for highway vehicles, but producers and distributors would not be required to provide 500 ppm (or 15 ppm) diesel fuel for non-highway usage. The higher cost of producing 500 ppm fuel might discourage an oversupply. The extent of any 500 ppm fuel produced for non-highway uses depends on the refiners' decisions whether to produce 500 ppm fuel for the highway market, as well as for the non-highway market. If the refiners in Alaska decide to not produce excess 500 ppm diesel fuel, a significant amount of diesel fuel in Alaska would still have a high sulfur content. Also, regardless of the sulfur content, producers and distributors would have to segregate and dye the fuel not destined for motor vehicle use, or pay the Federal fuel tax in accordance with the Internal Revenue Service requirements. As previously noted, the State of Alaska indicates that a large portion of the estimated high cost associated with distribution of 500 ppm diesel fuel is due to the EPA and Internal Revenue Service dye requirements for the non-highway fuel. However, if Alaska were to be exempt from those dye requirements, much of the high costs of segregating the fuels could be avoided and excess 500 ppm fuel for the non-highway market would be more economical. Our final rule grants Alaska a permanent exemption from the EPA dye requirements, but an exemption from the IRS dye requirement would require legislation by Congress. We understand that the Alaska congressional delegation is working on such legislation.

For reasons discussed in more detail in the following section, cross-border traffic is expected to raise an air quality issue for the lower-48 states and Canada. We are concerned about the impact on emissions in Canada and the lower-48 states of diesel vehicles and trucks from Alaska being driven to locations in Canada and the lower-48 states. We are also concerned about the impact on emissions in the lower-48 states, and of damage to the engines and emission control systems, of diesel vehicles and trucks from the lower-48 states driven to Alaska and refueled with high-sulfur fuel before returning to the lower-48 states.

c. Engine and emission control system factors

The impacts of using high-sulfur (>500 ppm) diesel fuel on current engine and emission control system technologies, and those anticipated that will be used to meet the 2004 emission standards, are discussed in our 1998 proposal (63 FR 23241, April 28, 1998) to grant Alaska a

permanent exemption from the diesel sulfur standard (500 ppm), and are not repeated here. The impacts of using diesel fuel with higher than 15 ppm sulfur on upcoming engine and emission control systems designed to meet the new 2007 emission standards are discussed in chapter III of this document.

In response to our 1998 proposal to grant Alaska a permanent exemption from the diesel fuel sulfur standard of 500 ppm, but prior to our announced action to propose more stringent emission standards for heavy-duty diesel engines and sulfur standard for highway diesel fuel of today's action, the Engine Manufacturers Association commented that, if we grant Alaska a permanent exemption for highway diesel fuel, the engine manufacturers should be exempted from the recall liability requirements and warranty liability requirements of Section 207 of the Clean Air Act for any engine affected by a fuel exemption in Alaska. The Engine Manufacturers Association stated that the engine manufacturers' ability to meet current and future emission standards, and the proper operation and durability of highway engines and after treatment technology, is dependent on the availability of 500 ppm (or the new low sulfur diesel fuel, depending on the applicable emission standards) diesel fuel.

In response to our preamble language in the August 1998 final rule to extend Alaska's sulfur exemption for nine months, the Engine Manufacturers Association commented that this is not a local issue, confined solely within Alaska's borders. It stated the 2004 engine technologies that will require 500 ppm diesel fuel will be used on all heavy-duty diesel engines, including those used in line-haul operations, and that vehicles from the lower-48 states and Canada with technologies requiring 500 ppm diesel fuel surely will deliver goods in Alaska. The Engine Manufacturers Association indicated that any exposure to Alaska high-sulfur diesel fuel may permanently reduce the effectiveness of the emission control technologies employed on those engines and substantially reduce their overall durability and performance. It further indicated that not only will the owners of those vehicles suffer damage (for which the engine manufacturer should not be responsible), but as a result, the lower-48 states and Canada will also suffer adverse and excessive emission contributions.

As discussed in Chapter III, we expect that these concerns of the Engine Manufacturers Association will be even greater for the upcoming engine technologies designed to meet the new 2007 emission standards for diesel motor vehicles and diesel motor vehicle engines, if they would be operated using diesel fuel with sulfur levels higher than 15 ppm. We are denying Alaska's petition for permanent sulfur exemption for the areas served by the Federal Aid Highway System. While we are not taking action in the final rule on the existing permanent sulfur exemption for the rural areas, both the rural areas and the areas served by the Federal Aid Highway System will be required to meet the new 15 ppm sulfur standard. However, we are allowing Alaska's 500 ppm exemptions to continue until the new 15 ppm sulfur standard becomes effective in 2006. Thus, today's action will fully address the concerns of the Engine Manufacturers Association in the long term, but only partially for the transition period.

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Consequently, the following comments pertain to the period when Alaska will still be covered by a diesel fuel sulfur exemption, and 500 ppm diesel fuel may not be available as in the rest of the nation.

Engine manufacturers previously expressed concern that, during the period of exemption, 2004 technology emission control equipment will likely be damaged, and those engine technologies using cooled-EGR will likely have increased wear, if they are operated using high-sulfur (>500 ppm) fuel in Alaska. The Alaska Trucking Association, which is the other stakeholder most directly impacted by the use of high sulfur fuel, commented in a 1998 letter that it is most concerned about the near-term cost of 500 ppm fuel. That association indicated that the Alaska market will provide 500 ppm fuel for those engines as needed, without a mandate from the state or federal government. It noted that Alaska's truck fleet is somewhat older than that of the lower-48 states, and the new technology engines (those designed to meet the 2004 emission standards) will likely not be "common" in Alaska's fleet until sometime after 2010. The Alaska Trucking Association recommended a five-year extension to the sulfur exemption and a subsequent "reasonable" transition period, after which 500 ppm diesel fuel would be required.

We are encouraging, but not requiring, Alaska to make 500 ppm diesel fuel available to the 2004 technology vehicles and trucks that need it during this period of exemption. We have learned that Tesoro is currently producing and supplying 500 ppm diesel fuel in Alaska. Therefore, for example, for those areas supplied by Tesoro (or other Alaska refiners that choose to produce 500 ppm sulfur diesel fuel, or distributors that choose to import 500 ppm sulfur diesel fuel), Alaska would need only to segregate and label enough of Tesoro's product for the new technology vehicles and trucks. In areas not served by Tesoro (or other Alaska refiners producing 500 ppm fuel, or distributors importing 500 ppm fuel), Alaska would need to transport some of the Tesoro fuel, or import some 500 ppm fuel from the lower-48 states as well.

In our June 2, 2000 proposal to establish a 15 ppm sulfur standard in 2006, as in previous actions to grant Alaska sulfur exemptions, we proposed to not base any recall on emissions exceedances caused by the use of high-sulfur (>500 ppm) fuel in Alaska during this period of exemption. Our in-use testing goals are to establish whether representative engines, when properly maintained and used, will meet emission standards for their useful lives. These goals are consistent with the requirements for recall outlined in Section 207(c)(1) of the CAA. Further, we believe that manufacturers may have a reasonable basis for denying emission related warranties where damage or failures are caused by the use of high-sulfur (>500 ppm) fuel in Alaska. These issues are addressed in the previous rules to grant Alaska extensions to its temporary exemption for Federal Aid Highway areas. In response to the proposal, the Engine Manufacturers Association commented that the level of protection provided to engine manufacturers under the current exemption for Alaska and the proposal, as described above, falls short of what is reasonable and necessary. It asserted that the use of high sulfur diesel fuel by an engine should raise a "rebuttable presumption" that the fuel has caused the engine failure, and

that EPA should have the burden of rebutting that presumption. It also asserted that the emissions warranty is a regulatory requirement under Section 207, that only EPA has the authority to exclude claims based on the use of high sulfur diesel fuel.

We understand and concur with the manufacturers' concerns about in-use testing of engines operated in an area exempt from fuel sulfur requirements. Consequently, we affirm that, for recall purposes, we will not seek to conduct or cause the in-use testing of engines we know have been exposed to high sulfur fuels. We will likely screen any engines used in our testing program to see if they have been operated in the exempt area. We believe we can readily obtain sufficient samples of engines without testing engines from exempt areas. Also, in any recall that we order, manufacturers have the option to request a public hearing under §85.1807(b)(ii). The use of engines that have seen high sulfur fuel would increase the likelihood that EPA would grant a request for a recall hearing. We would expect manufacturers to scrutinize any test engines for sulfur usage that were used to justify an ordered recall. In reviewing the warranty concerns of the Engine Manufacturers Association, we have determined that our position regarding warranties, as previously stated and described above, is consistent with section 207(a) and (b) of the CAA and does not require any new or amended regulatory language to implement.

Subsequent to the 1995 petition for a permanent exemption from the diesel fuel sulfur (500 ppm) requirements, the Engine Manufacturers Association requested enforcement discretion regarding the removal of catalytic converters because of an indicated plugging problem caused by the high-sulfur (>500 ppm) diesel fuel in Alaska. However, information subsequently collected by us from several heavy-duty engine manufacturers demonstrates that catalyst plugging is mainly a cold weather problem and not a high-sulfur fuel issue. We are also aware that the majority of the plugged catalysts have been eliminated. In a September 19, 1997 letter to us, the Engine Manufacturers Association indicated that the immediate problems that led to the Engine Manufacturers Association's earlier request have been resolved, although the manufacturers indicate they continue to have concerns.

The Engine Manufacturers Association commented in response to the 1998 proposal that, as a result of the 2004 emission standards, heavy-duty engine manufacturers will likely introduce EGR systems on their engines and may also, if fully developed, use NO_x catalysts. In the EGR system, exhaust gas is recirculated back into the cylinder to reduce the amount of fresh charge air or oxygen available for combustion during certain operating conditions. When the engine is operated on high-sulfur (>500 ppm) fuel, sulfur in the exhaust gas stream is condensed by the EGR cooler and forms sulfuric acid deposits in the cooler. The Engine Manufacturers Association claims these sulfuric acid deposits will significantly contribute to the deterioration of the EGR system and cause decreased engine durability. Similar to oxidation catalysts, the NO_x catalyst will be adversely affected if operated on high-sulfur (>500 ppm) diesel fuel. The Engine Manufacturers Association claims that a special concern regarding NO_x catalysts is the fact that a

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single exposure to high-sulfur (>500 ppm) diesel fuel will likely poison the catalyst, causing it to lose its emissions reduction effectiveness permanently.

The Engine Manufacturers Association further commented that, under an exemption from the sulfur content (500 ppm) for highway diesel fuel, manufacturers should be allowed to sell engines without catalysts or exhaust gas recirculation (EGR) systems, and to continue to sell older technology heavy-duty engines (i.e., without catalysts or EGR systems). It also commented that users of vehicles in which 1994 and later model year heavy-duty engines are placed should be exempted from tampering liability and be allowed to remove plugged catalysts. The Engine Manufacturers Association is concerned that using a high-sulfur (>500 ppm) content fuel over a long period of time may have a tendency to cause plugging of catalysts, which could lead to more serious engine malfunction and warranty claims. The Engine Manufacturers Association asserts that vehicle owners are already experiencing engine failures directly resulting from catalyst plugging. and that the plugging is substantially aggravated when the vehicle is operated in extremely cold temperatures.

We also are concerned about these problems, but do not believe it is necessary to offer an exemption that allows the removal of catalysts in the field, or that permits manufacturers to introduce into commerce catalyzed-engines without catalysts. In response to the June 2000 proposal for today's action, we received no additional information about in-use catalyst plugging and engine failures being caused by the use of high-sulfur (>500 ppm) diesel fuel, or any data and descriptions of remedies. Also, as previously discussed, we have indicated we do not intend to use vehicles from Alaska to show noncompliance by those engines for the purpose of recalling an engine class, and that the engine manufacturers have a reasonable basis for denying warranty coverage where the problems are due to the use of high-sulfur (>500 ppm) diesel fuel.

d. Are there alternatives to granting or denying Alaska's Petition for permanent exemption?

The Alaska Center for the Environment suggested in an April 23, 1996 letter, and the Trustees supported, three fall back positions. While they strongly advocated that we deny Alaska's request for a permanent sulfur exemption, they preferred one or a combination of the three fallback positions rather than a permanent exemption. They believed that the fall back alternatives would achieve some air quality benefits at reduced cost compared to full compliance with the fuel sulfur requirement (500 ppm). The first alternative would permanently exempt most of Alaska, but not Southeast Alaska. Southeast Alaska does not need the low cloud point diesel fuel in the winter, and it was assumed at that time (but no longer true) that Southeast Alaska imports most of its diesel fuel from the lower-48 states. The Alaska Center for the Environment claimed that 500 ppm diesel fuel from the lower-48 states could easily be substituted for high sulfur (> 500 ppm) diesel fuel currently being imported before shipping it to Southeast Alaska. The second alternative would permanently exempt Alaska in the summer

months, when conventional diesel fuel is generally used, but not in the winter months when Jet-A kerosene is generally used. The Alaska Center for the Environment claimed the problem of supplying 500 ppm fuel in the winter, when low-cloud point fuel is needed, could be avoided. The third alternative would require lower sulfur (but generally greater than 500 ppm) Jet-A kerosene year round. The Alaska Center for the Environment claimed some air quality benefits might be achieved by using fuel that is already available in Alaska.

In general, we believe some assumptions upon which each of these alternatives were based are erroneous or no longer applicable because of recent information or changes to the emission standards and fuel requirements in the final rule. We now believe these alternatives would not likely achieve significant cost reductions, or significant air quality benefits, or protect the upcoming engine technologies from reduced performance and damage. In response to the 1998 proposal, no other stakeholder indicated they were in favor of these alternatives, and refiners and the Alaska Department of Environmental Conservation submitted comments indicating they are opposed to these alternatives because of cost or lack of air quality benefits. Since no other stakeholder supported these alternatives, and since the situation has changed with the new standards, and since we are not granting Alaska's request for a permanent exemption for the areas covered by the Federal Aid Highway System, we believe that these alternatives need not be addressed further.

The Trustees also noted in its 1998 comments, that when we granted Alaska's rural areas a permanent exemption from the 500 ppm diesel fuel requirements, we reserved the right to withdraw the exemption in the future if circumstances change such that the exemption is no longer appropriate. The Trustees commented that in light of Canada's promulgation of 500 ppm diesel fuel requirements, Petro Star's commitment to produce 500 ppm diesel fuel, recent health studies that concretely link SO₂ and diesel exhaust with respiratory problems and risks of cancer, and worldwide acceptance of the 500 ppm sulfur content limit, we should not only deny Alaska's current petition for the areas served by the Federal Aid Highway System, we should also reconsider Alaska's exemption for the rural areas.

e. What Flexibility Are We Offering Alaska?

The Federal Register notice for the final rule fully discusses our flexibility option for Alaska. In summary, as mentioned above, Alaska has submitted a petition for a permanent exemption from the 500 ppm standard for areas not served by the Federal Aid Highway System. We are not taking action on that petition in the final rule. Our goal is to take action on that petition in a way that minimizes costs through Alaska's transition to the low sulfur (15 ppm) program. The cost of compliance could be reduced if Alaska refiners were given the flexibility to meet the low sulfur standard in one step (i.e., going straight from uncontrolled levels to the 15 ppm standard), rather than in two steps (i.e., once for the current 500 ppm sulfur standard in 2004 when the temporary exemption expires, and again for the 15 ppm standard in 2006). Therefore,

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we are extending the existing temporary exemption from the current sulfur standard of 500 ppm for the areas of Alaska served by the Federal Aid Highway System from January 1, 2004 (the current expiration date) to the effective date for the new 15 ppm sulfur standard (i.e., June 1, 2006 at the refinery level; July 15, 2006 at the terminal level; and September 1, 2006 at all downstream locations).

Also, because of the unique circumstances in Alaska, we are offering an alternative option for implementing the low sulfur (15 ppm) fuel program in Alaska. We are providing the State an opportunity to develop an alternative low sulfur transition plan for Alaska. This plan will need to ensure that sufficient supplies of low sulfur (15 ppm) diesel fuel are available in Alaska to meet the demand of any new 2007 and later model year diesel vehicles. Given that Alaska's demand for highway diesel fuel is very low and only a small number of new diesel vehicles are introduced each year, it may be possible to develop an alternative implementation plan for Alaska in the early years of the program that provides low sulfur (15 ppm) diesel only in sufficient quantities to meet the demand from the small number of new diesel vehicles. This would give Alaska refiners more flexibility during the transition period because they would not have to desulfurize the entire highway diesel volume, or even the levels required under the temporary compliance option described in the Federal Register notice for the final rule. Our goal in offering this additional flexibility is to transition Alaska into the low sulfur (15 ppm) fuel program in a manner that does not compromise the environmental benefits of the program by ensuring that the new vehicles receive the low sulfur fuel they need, while minimizing costs. We expect that the transition plan would begin to be implemented at the same time as the national program, but the State will have an opportunity to determine what volumes of 15 ppm fuel will need to be supplied, and in what timeframes, in different areas of the State.

At a minimum, this transition plan will need to: 1) ensure an adequate supply (either through production or imports of 15 ppm fuel to meet the demand of any 2007 or later model year vehicles), 2) ensure sufficient retail availability of low sulfur fuel for new vehicles in Alaska, 3) address the growth of supply and availability over time as more new vehicles enter the fleet, 4) include measures to ensure segregation of the 15 ppm fuel, prevent contamination, and prevent misfueling, and 5) ensure enforceability. We anticipate that, to develop a workable transition plan, the State will likely work in close cooperation with refiners and other key stakeholders, including retailers, distributors, truckers, engine manufacturers, environmental groups, and other interested groups. In the Federal Register Notice for the final rule, we discuss this option in more detail, including the timeframe for the State to submit the plan and for EPA to approve it.

If the State anticipates that the primary demand for 15 ppm fuel will be along the highway system (e.g., to address truck traffic from the lower-48 states) in the early years of the program, then the initial stages of the transition plan could be focused in these areas. We believe it would be appropriate for the State to consider an extended transition schedule for implementing the low

sulfur program in rural Alaska, as part of the state's overall plan, based on when they anticipate the introduction of a significant number of 2007 and later model year vehicles in the remote areas. While we are not taking action in the final rule on the existing permanent exemption from the 500 ppm standard for the rural areas, both the rural areas and the areas served by the Federal Aid Highway System will be required to meet the new 15 ppm sulfur standard, with the opportunity to develop a transition plan for how the new standard will be implemented as discussed above.

During this transition period, it is possible that both 15 ppm (for 2007 and later model year vehicles) and higher sulfur (for older vehicles) highway fuels might be available in Alaska. To avoid the two-step sulfur program described above during an alternative transition period, we would consider additional extensions to the temporary exemption of the 500 ppm standard beyond 2006 (e.g., for that portion of the highway diesel pool that is available for the pre-2007 vehicles during Alaska's transition period). We would make a decision on any additional temporary extensions, if appropriate, in the context of the separate rulemaking taking action on the alternative transition plan submitted by Alaska (as described in the Federal Register Notice for the final rule).

As in previous actions to grant Alaska sulfur exemptions, we will not base any vehicle or engine recall on emissions exceedences caused by the use of high-sulfur (>500 ppm) fuel in Alaska during the period of the temporary sulfur exemption. In addition, manufacturers may have a reasonable basis for denying emission related warranties where damage or failures are caused by the use of high-sulfur (>500 ppm) fuel in Alaska.

Finally, the costs of complying with both the current 500 ppm sulfur and new 15 ppm sulfur diesel fuel standards could be reduced significantly if Alaska were not required to dye the non-highway fuel. Dye contamination of other fuels, particularly jet fuel, is a serious potential problem. This is a serious issue in Alaska since the same transport and storage tanks used for jet fuel (which are more than half of Alaska's distillate market) are generally also used for other diesel products, including off-highway diesel products which are required to be dyed under the current national program. This issue is discussed further above. Therefore, we also are granting Alaska's request for a permanent exemption from the dye requirement of 40 CFR 80.29 and 40 CFR 80.446 for the entire State.

C. American Samoa, Guam, and Commonwealth of Northern Mariana Islands (CNMI)

1. Why Are We Considering an Exemption for American Samoa, Guam, and CNMI?

Prior to the effective date of the current highway diesel sulfur standard of 500 ppm, the territories of American Samoa, Guam and CNMI petitioned EPA under section 325 of the CAA for an exemption from the sulfur requirement under section 211(i) of the CAA and associated regulations at 40 CFR 80.29. The petitions were based on geographical, meteorological, air quality, and economic factors unique to those territories. We subsequently granted the petitions.^f We are now revisiting the issue of diesel sulfur exemptions for these territories, because this rule impacts these territories, either directly by requiring stringent sulfur requirements or indirectly by the future impact of using high-sulfur diesel fuel in upcoming technologies for diesel vehicles and engines.

2. What are the Relevant Factors?

a. American Samoa

American Samoa is a group of five volcanic islands and two coral atolls located in Polynesia, approximately 2,300 miles southwest of Hawaii and 1,600 miles northeast of New Zealand. It has a total land area of approximately 76 square miles, about two-thirds of which is mountainous with steep slopes that make it virtually inaccessible. The population was about 52,400 in 1993. Over 96 percent of the population live on the largest island, Tutuila, which is approximately 53 square miles. The air quality is generally pristine, due to the combined prevailing winds, climate, remoteness, and low population. American Samoa is classified EPA "Priority III" for all pollutants. Continuing the existing diesel sulfur exemption or expanding it to the new diesel sulfur standard would not cause an increase in emissions, but would forego a small emissions benefit if American Samoa used low sulfur diesel fuel for its highway vehicles. There are no cross border issues.

Total diesel fuel imports and consumption is about 38,600,000 gallons per year. The 60 diesel fueled vehicles licensed for highway use (in 1991) use approximately 0.12 percent, 46,000 gallons per year. The fishing fleet uses approximately 70 percent, or 27,000,000 gallons per year. Power generation uses approximately 18 percent, or 7,000,000 gallons per year. Tuna Canneries use approximately 10 percent, or 4,000,000 gallons per year in boilers for steam generation.

^f See 57 FR 32010, July 20, 1992 for American Samoa;; 57 FR 32010, July 20, 1992 for Guam; and 59 FR 26129, May 19, 1994 for CNMI

Other uses (stand-by generators and small engines) consume a small quantity. American Samoa has two providers of diesel fuel. Mobil Australia provides about 70 percent and Tesoro Hawaii provides about 30 percent. All petroleum is shipped to American Samoa by medium range tankers.

The economy of American Samoa is ill suited to handling the additional expense of low sulfur diesel fuel and upgrades to its storage and distribution system. It lacks internal petroleum supplies and refining capabilities. Diesel fuel must be imported over long distances and in small cargo parcels, making the cost about 10 cents per gallon higher than in the mainland United States (exclusive of the effects of taxes). It was estimated in 1991 that shipping a segregated quantity of low sulfur diesel fuel would cost an additional eight to ten cents per gallon. The new 15 ppm sulfur standard would add additional cost to the low sulfur fuel. Compliance with low sulfur requirements for highway fuel would require construction of separate storage and handling facilities. American Samoa, which owns the petroleum storage facilities, would have to construct a new storage tank and fuel lines at an estimated 1991 cost of \$550,000.

If American Samoa alternatively decided to use low sulfur fuel for all purposes to avoid segregation, compliance with low sulfur requirements would, in effect, bar importation of diesel fuel by the only suppliers in the area outside of Tesoro. The effect of a monopoly from prior years' experience was to see an increase in the price of fuels by four to five cents per gallon. While Australia, Philippines and certain other Asian countries have or will soon require low sulfur diesel fuel, they require a 500 ppm sulfur limit, not the new 15 ppm sulfur limit established by today's action for the United States.

The fishing fleet buys its fuel in Samoa, but has the alternative to fuel in Fiji or from tankers at sea. If the cost of fuel in American Samoa increased, the fishing fleet would probably significantly reduce its fueling in American Samoa resulting in a "disastrous decline in the local economy and lost revenues to the government." In 1997, the price of fuel in Samoa rose to over ten cents a gallon higher than the price in Fiji, and Samoa lost about one-half of its sales to the fleet. Currently, the price of diesel fuel is about six to seven cents per gallon higher than in Fiji. Any additional fuel switching by the fleet due to a low sulfur requirement would damage the economy without providing any significant improvement in air quality.

Any increased fuel costs of producing steam by the canneries would be another competitive disadvantage for them to remain in American Samoa. Cheap labor and fuel in the Philippines and Thailand have attracted canneries to those countries that compete directly with the canneries in American Samoa. Over the past eight years, Samoa has granted larger and larger tax exemptions to retain the canneries in Samoa.

b. Guam

Guam is the southern-most island in the Marianas Archipelago, located in Polynesia, approximately 3,700 miles west-southwest of Honolulu and 1,550 miles south of Tokyo. The island is about 28 miles long and between 4 and 8.5 miles wide, with a total land area of about 209 square miles. In the early 1990's, the population was 133,152.

Guam is in attainment with the primary NAAQS with the exception of sulfur dioxide in two areas. One area is a radius of 3.5 km around the Piti Power Plant. The other area is a radius of 3.5 km around Tanguisson. Both areas are designated nonattainment for sulfur dioxide as a result of monitored and modeled exceedences in the 1970's prior to implementing changes to power generation facilities. Guam believes the area around Piti is now in attainment. The Tanguisson area includes only two small villages and a U.S. Air Force Annex, none of which attract significant vehicle traffic.

In the early 1990's, there were 735 registered diesel-fueled motor vehicles, approximately one percent of the total vehicle population on Guam. On an annual basis, the diesel-fueled vehicles on Guam were estimated in 1993 to emit less than 0.1 percent of the maximum potential sulfur dioxide emissions from other sources, given the 6000 ppm (maximum) level of sulfur in diesel fuel at that time. Therefore, Guam's continued use of 6000 ppm (maximum) diesel fuel is not expected to have any significant impact on the ambient air quality status of Guam, including the status of the two areas designated as nonattainment for sulfur dioxide. Continuing the existing diesel sulfur exemption or expanding it to the new diesel sulfur standard would not cause an increase in emissions, but would forego a small emissions benefit if Guam used low sulfur diesel fuel for its highway vehicles. There are no cross border issues.

The economy of Guam is ill suited to handling the additional expense of low sulfur diesel fuel and upgrades to its storage and distribution system. It lacks internal petroleum supplies and refining capabilities and relies on long distance imports. Essentially all of the island's petroleum products were refined in Singapore in the early 1990's, but there were four sources: Singapore, Indonesia, Australia and the Philippines. While Australia, Philippines and certain other Asian countries have or will soon require low sulfur diesel fuel, they require a 500 ppm sulfur limit, not the new 15 ppm sulfur limit required by today's action for the United States. In 1992, the No. 2 diesel fuel imports had sulfur content ranging between 3,900 to 5,000 ppm and cetane ranging from 48 to 55.

If stationary sources continue to use high-sulfur diesel fuel, importing low sulfur diesel fuel would require the costly construction of separate storage facilities. Even if Guam were to import low sulfur diesel fuel for all its diesel needs from the United States mainland to avoid the need to segregate the highway fuel, new storage facilities would be necessary to store larger quantities of fuel, since shipments would be less frequent and possibly less reliable, due to the

increased round-trip distances. It was estimated that Guam's fuel suppliers could conceivably be subjected to \$14,500,000 and \$22,300,000 annually to comply with the low sulfur requirement, and the cost per gallon of diesel fuel could increase by 30-46 cents per gallon. This high cost of compliance is due to additional transportation costs associated with importing fuel from the mainland, construction of new storage facilities needed to segregate low sulfur and high sulfur fuel, and to store larger quantities of fuel, and the higher purchase price of the low sulfur [500 ppm] fuel. The new 15 ppm sulfur standard would add additional cost to the low sulfur fuel.

c. Commonwealth of Northern Mariana Islands (CNMI)

CNMI consists of 14 islands of volcanic origin that extend in a general north-south direction for 388 nautical miles, with a land area of 176.5 square miles. It lies in the western part of the Pacific Ocean about 1150 miles south of Tokyo, 108 miles north of Guam, and 5280 miles from the United States mainland. Development and the population of Saipan, the most populated island, are predominately on the western side. The population centers exist on Saipan (38,896), Tinian (2,118), and Rota (2,295). The northern islands of the commonwealth have a population of about 36 people.

The development being concentrated on the west side, meteorology (westward trade winds) and lack of heavy industry have a beneficial impact on CNMI's air quality. As of 1994, CNMI was in attainment with all primary NAAQS. The islands have approximately 200 miles of roads, of which approximately 50 percent are paved, and about 500 diesel vehicles, of which about 60 are owned by the CNMI government. Continuing the existing diesel sulfur exemption or expanding it to the new sulfur standard would not cause an increase in emissions, but would forego a small emissions benefit if CNMI used low sulfur diesel fuel for its highway vehicles. There are no cross border issues.

Saipan has two bulk storage facilities for diesel fuel, and Rota and Tinian each have one. The main use of diesel fuel is for electrical power generation. CNMI relies exclusively on diesel fuel to provide electrical power. An insignificant amount of the diesel fuel is used for motor vehicles. CNMI lacks internal petroleum supplies and refining capabilities and relies on long distance imports. At the time of the request for exemption, CNMI relied on the importation of fuels exclusively from refineries in Singapore. While Australia, Philippines and certain other Asian countries have or will soon require low sulfur diesel fuel, they require a 500 ppm sulfur limit, not the new 15 ppm sulfur limit required by today's action for the United States.

The economy of CNMI is ill suited to handling the additional expense of low sulfur diesel fuel and upgrades to its storage and distribution system. The cost of diesel fuel on Saipan is approximately 20 cents per gallon higher than that on the United States mainland [1994]. The cost of diesel fuel on Rota and Tinian are higher than on Saipan. In order to meet the sulfur requirement, it was estimated that low sulfur (500 ppm) diesel fuel would have to be imported

from the United States at a cost increase of 10 to 20 cents per gallon. The new 15 ppm sulfur standard would add additional cost. A fuel supplier on CNMI estimated that in order to comply with the low sulfur diesel fuel standard, four new storage tanks would need to be built for the three [populated] islands at a cost of \$2,000,000. Because of the added costs of shipping materials to CNMI for construction projects, construction costs on CNMI are generally 20 to 40 percent higher than those of the United States mainland.

3. What Are the Options for the Territories?

We could include or exclude the territories in the geographical areas for which the new diesel fuel sulfur standard applies. As in the early 1990's with the 500 ppm sulfur standard, we believe that compliance with the new 15 ppm sulfur standard would result in small environmental benefit, but major economic burden. We are also concerned about the impact to vehicle owners and operators if new engine and emission control technologies were run using high-sulfur fuel. We believe that for the sulfur exemption to be viable to vehicle owners and operators, they would need access to either low sulfur fuel or pre-2007 technology vehicles that could be run on high-sulfur fuel without significant engine damage or performance degradation. Consequently, the territories will either need to be exempted from both the new fuel and vehicle emission standards, or neither. Exempting them from only the fuel requirement would virtually preclude the sale of new vehicles in the territories due to their sulfur sensitivity.

4. What Flexibility are we Offering the Territories?

As we proposed, today's action excludes American Samoa, Guam and the Commonwealth of Northern Mariana Islands from the new diesel fuel sulfur requirement of 15 ppm and the 2007 heavy-duty diesel vehicle and engine emissions standards, and other requirements associated with those emission standards. The territories will continue to have access to 2006 heavy-duty diesel vehicle and engine technologies, at least as long as manufacturers choose to market those technologies. We will not, however, allow the emissions control technology in the territories to backslide from those available in 2006. If, in the future, manufacturers choose to market only heavy-duty diesel vehicles and engines with 2007 and later emission control technologies, we believe the market will determine when and if the territories will make the investment needed to obtain and distribute the low sulfur diesel fuel necessary to support these technologies.

This exclusion from emission standards does not apply to the new heavy-duty gasoline engine and vehicle emission standards because low sulfur gasoline that complies with our regulations will be available, and so concerns about damage to engines and emissions control systems will not exist. This exclusion from emission standards also does not apply to light-duty diesel vehicles and trucks because gasoline vehicles and trucks meeting the emission standards and capable of fulfilling the same functions will be available. We believe that the market will

determine when and if having access to new light-duty diesel technologies, in place of or in addition to gasoline technologies, is important enough to obtain and distribute the low sulfur diesel fuel needed to support those technologies.

As we also proposed, we are requiring all heavy-duty diesel motor vehicles and engines for these territories to be certified and labeled to the applicable requirements (either to the 2006 model year standards and associated requirements under the exclusion, or to the standards and associated requirements applicable for the model year of production under the nationwide requirements) and warranted, as otherwise required under the Clean Air Act and EPA regulations. Special recall and warranty considerations due to the use of excluded high sulfur fuel are the same as those for Alaska during its exemption and transition periods (see the discussion in previous section). To protect against this exclusion being used to circumvent the emission requirements applicable to the rest of the United States (i.e., continental United States, Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands) after 2006 by routing exempted (pre-2007 technology) vehicles and engines through one of these territories, we are restricting the importation of vehicles and engines from these territories into the rest of the United States. After the 2006 model year, diesel vehicles and engines certified under this exclusion to meet the 2006 model year emission standards for sale in American Samoa, Guam and the Commonwealth of the Northern Mariana Islands will not be permitted entry into the rest of the United States.

Appendix A: Legal Authority for Diesel Fuel Sulfur Control

We are promulgating diesel sulfur controls pursuant to our authority under Section 211(c)(1) of the Clean Air Act. This section gives us the authority to “control or prohibit the manufacture, introduction into commerce, offering for sale, or sale” of any fuel or fuel additive (A) whose emission products, in the judgment of the Administrator, cause or contribute to air pollution “which may be reasonably anticipated to endanger the public health or welfare” or (B) whose emission products “will impair to a significant degree the performance of any emission control device or system which is in general use, or which the Administrator finds has been developed to a point where in a reasonable time it would be in general use” were the fuel control or prohibition adopted. The following sections describe current regulatory requirements that affect diesel sulfur content, and explain our bases for controlling diesel sulfur under Section 211(c)(1). This section contains a summary of the issues. Refer to the Preamble and RIA for more details.

A. EPA’s Current Regulatory Requirements for Diesel

We currently have regulatory requirements for diesel fuel adopted under Sections 211(c) and 211(i) of the Act. Section 211(i)(1) prohibits the manufacture, sale, supply, offering for sale or supply, dispensing, transport, or introduction into commerce of motor vehicle diesel fuel which contains a concentration of sulfur in excess of 0.05 percent by weight, and which fails to meet a cetane index minimum of 40, or aromatics maximum of 35 percent beginning October 1, 1993. Section 211(i)(2) requires the Administrator to promulgate regulations to implement and enforce the requirements of section 211(i)(1), and authorizes the Administrator to require that diesel fuel not intended for motor vehicles be dyed in order to segregate that fuel from motor vehicle diesel fuel. See 40 CFR §80.29.

B. How the Proposed Diesel Sulfur Control Program Meets the CAA Section 211(c) Criteria

Under Section 211(c)(1), EPA may adopt a fuel control if at least one of the following two criteria is met: 1) the emission products of the fuel cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare, or 2) the emission products of the fuel will significantly impair emissions control systems in general use or which would be in general use were the fuel control to be adopted. We are promulgating controls on sulfur levels in diesel fuel based on both of these criteria. Under the first criterion, we believe that emissions

products of sulfur in diesel fuel used in heavy-duty engines contribute to PM pollution. Under the second criterion, we believe that sulfur in diesel fuel will significantly impair the emissions control systems expected to be used in heavy-duty engines designed to meet proposed emissions standards. The following sections summarize our analysis of each criterion.

1. Health and Welfare Concerns of Air Pollution Caused by Sulfur in Diesel Fuel

We believe that the emission products of diesel sulfur contribute to air pollution that can reasonably be anticipated to endanger public health and welfare. Sulfur in diesel fuel leads directly to emissions of SO₂ and sulfate PM from the exhaust of diesel vehicles. SO₂ emissions from diesel engines are directly proportional to the amount of sulfur in the fuel. SO₂ is oxidized in the atmosphere to SO₃ which then combines with water to form sulfuric acid (H₂SO₄) and further combines with ammonium in the atmosphere to form ammonium sulfate aerosols. These aerosols are what is often referred to as sulfate PM. This sulfate PM comprises a significant portion of the “secondary” PM that does not come directly from the tailpipe, but is nevertheless formed in the atmosphere from exhaust pollutants. Exposure to secondary PM may be different from that of PM emitted directly from the exhaust, but the health concerns of secondary PM are just as severe as for directly emitted particulate matter, with the possible exception of the carcinogenicity concerns with diesel PM.

Approximately 1-2 percent of the sulfur in diesel fuel is not converted into SO₂, but is instead further oxidized into SO₃ which then forms sulfuric acid aerosols (sulfate PM) as it leaves the tailpipe. While only a small fraction of the overall sulfur is converted into sulfate emissions in the exhaust of diesel vehicles today, it nevertheless accounts for approximately 10 percent of the total PM emissions from diesel engines today. Furthermore, with the application of the exhaust emission control devices that will be necessary to meet either the PM or NO_x emission standards in 2007, the conversion rate of sulfur in the fuel to sulfate PM in the exhaust increases dramatically. This sulfate PM is directly proportional to the sulfur concentration in the fuel. The health and welfare implications of the emissions of these compounds are discussed in greater detail in Section II of the Preamble and RIA.

Section 211(c)(2)(A) requires that, prior to adopting fuel controls based on a finding that the fuel’s emission products contribute to air pollution that can reasonably be anticipated to endanger public health or welfare, EPA consider “all relevant medical and scientific evidence available, including consideration of other technologically or economically feasible means of achieving emission standards under [section 202 of the Act].” EPA’s analysis of the medical and scientific evidence relating to the emissions impact of emissions from diesel vehicles which are affected by sulfur in diesel fuel is described in more detail in Sections II of the Preamble and RIA.

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EPA has also satisfied the statutory requirement to consider “other technologically or economically feasible means of achieving emission standards under section [202 of the Act].” This provision has been interpreted as requiring consideration of establishing emissions standards under § 202 prior to establishing controls or prohibitions on fuels or fuel additives under § 211(c)(1)(A). See *Ethyl Corp. v. EPA*, 541 F.2d. 1, 31-32 (D.C. Cir. 1976). In *Ethyl*, the court stated that § 211(c)(2)(B) calls for good faith consideration of the evidence and options, not for mandatory deference to regulation under § 202 compared to fuel controls. *Id.* at 32, n.66.

In today’s action, EPA is finalizing standards for fuels and vehicles together. Thus, it is first important to consider that the sulfur standards are not being promulgated as an alternative to emissions standards, but in addition to such standards, and as a necessary prerequisite to ensuring that heavy-duty engines can meet the engine standards. In addition, the heavy-duty emission standards being finalized today will begin with the 2007 model year, and even at that time, many older technology heavy-duty vehicles will still be on the road. Thus, another point to consider is that the emissions standards under § 202 will achieve smaller emissions benefits in the early years of the program and will not achieve their full emissions benefits for a number of years, while the sulfur standards will begin achieving some emissions benefits immediately through reducing emissions from the existing fleet of motor vehicles.

EPA has also considered more stringent emissions standards under § 202 as an alternative to regulating diesel sulfur. However, for the reasons described in Section III of the Preamble and RIA, the Agency concludes that the heavy-duty emission standards represent the levels of emission control that are economically and technologically feasible from heavy-duty engines and vehicles beginning in 2007. Moreover, EPA considered heavy-duty standards alone as an alternative to regulating diesel sulfur. However, as described in Preamble Section III, the Agency concludes that the heavy-duty standards would not be feasible without control of diesel sulfur. For these reasons, EPA finds that the alternatives of either more stringent engine and vehicle standards, or engine and vehicle standards without sulfur control, are not technologically or economically feasible options to regulating diesel sulfur.

EPA’s consideration of other technologically and economically feasible means of achieving emissions standards under § 202 of the Act supports the conclusion that the diesel sulfur standards finalized today represent an appropriate exercise of the Agency’s discretion under § 211(c)(1)(A), even when the heavy-duty engine and vehicle standards are considered.

2. Impact of Diesel Sulfur Emission Products on Emission Control Systems

EPA believes that sulfur in diesel fuel can significantly impair the emissions control technology of engines designed to meet the final emissions standards. We know that diesel sulfur has a negative impact on vehicle emission controls. This is not a new development. As

discussed in Section III of the Preamble to the final rule, aftertreatment technologies exist that we believe will be capable of achieving dramatic reductions in NO_x and PM emissions from diesel engines for the 2007 model year. The aftertreatment technology for PM is already in an advanced state of development and being tested in diesel vehicle fleet demonstrations in the U.S. and Europe. The NO_x adsorber aftertreatment technology, while already in commercial use in other applications is in a comparatively earlier state of development for use on diesel vehicles, but as discussed in Section III of the preamble and RIA, tremendous progress is already being made and EPA believes the lead time between now and 2007 will provide ample opportunity to bring this technology into the diesel vehicle marketplace. EPA believes that these PM and NO_x aftertreatment technologies will be in general use on diesel vehicles by MY 2007, with the diesel sulfur controls adopted in this rule.

These aftertreatment technologies are ineffective in reducing NO_x and PM emissions and incapable of being introduced widely into the marketplace at the diesel fuel sulfur concentrations typical today. Not only does their efficiency at reducing NO_x and PM emissions fall off dramatically at elevated fuel sulfur concentrations, but vehicle driveability impacts and permanent damage to the aftertreatment systems are also possible.

In order to ensure passive regeneration of the diesel particulate filter as described in Section III of the Preamble and RIA, we are expecting that significant amounts of precious group metals (primarily platinum) will be used in their washcoat formulations. There are two primary mechanisms by which sulfur in diesel fuel can limit the effectiveness or robustness of diesel particulate filters which rely on an oxidizing catalyst function from platinum. The first is inhibition of the oxidation of NO to NO₂ and the second is the preferential oxidation of SO₂ to SO₃, resulting in production of sulfate particulate matter.

All of the NO_x aftertreatment technologies discussed in Section III of the Preamble and RIA are expected to utilize platinum to oxidize NO to NO₂ to improve the NO_x reduction efficiency of the catalysts at low temperatures. In the case of the NO_x absorber, conversion of NO to NO₂ is also an essential part of the process of NO_x storage. This reliance of NO₂ as an integral part of the reduction process means that the functioning of the NO_x aftertreatment technologies, like the PM aftertreatment technologies, will be significantly impaired by sulfur in diesel fuel.

3. Sulfur Levels that Exhaust Aftertreatment for Heavy-Duty Vehicles Can Tolerate

As discussed in Section III.F. of the Preamble, there are three key factors which when taken together lead us to believe that a diesel fuel sulfur cap of 15 ppm is necessary so that the NO_x and PM aftertreatment technology on diesel engines will function properly and be able to meet the emission standards. These factors, as discussed in more detail in Section III of the

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Preamble and RIA, are the implications of sulfur levels in excess of 15 ppm on the efficiency and reliability of the systems and their impact on the fuel economy of the vehicle.

The efficiency of emission control technologies at reducing harmful pollutants is directly impacted by sulfur in diesel fuel. Initial and long term conversion efficiencies for NO_x, HC, CO and diesel PM emissions are significantly reduced by catalyst poisoning and catalyst inhibition due to sulfur. NO_x conversion efficiencies with the NO_x adsorber technology in particular are dramatically reduced in a very short time due to sulfur poisoning of the NO_x storage bed. In addition total PM control efficiency is negatively impacted by the formation of sulfate PM. The formation of sulfate PM is likely to be in excess of the total PM standard proposed today, unless diesel fuel sulfur levels are no higher than 15 ppm. When sulfur is kept at these low levels, both PM and NO_x aftertreatment devices are expected to operate at high levels of conversion efficiency, allowing compliance with the PM and NO_x emissions standards.

The reliability of the emission control technologies to continue to function as required under all operating conditions for the life of the vehicle is also directly impacted by sulfur in diesel fuel. As discussed in Section III of the Preamble and RIA, sulfur in diesel fuel can prevent proper operation and regeneration of both NO_x and PM control technologies leading to permanent loss in emission control effectiveness and even catastrophic failure of the systems. For example, if regeneration of a PM filter does not occur, catastrophic failure of the filter will occur. We believe, based on information available to us, that diesel fuel sulfur levels of 15 ppm are needed and would allow these technologies to operate properly throughout the life of the vehicle, including proper periodic or continuous regeneration .

The sulfur content of diesel fuel will also impact the fuel economy of vehicles equipped with NO_x and PM aftertreatment technologies. As discussed in detail in Section III of the Preamble and RIA, NO_x adsorbers are expected to consume diesel fuel in order to cleanse themselves of stored sulfates and maintain efficiency. The larger the amount of sulfur in diesel fuel, the greater this impact on fuel economy. Likewise PM trap regeneration is inhibited by sulfur in diesel fuel. This leads to increased PM loading in the diesel particulate filter, increased exhaust backpressure, and poorer fuel economy. Thus for both NO_x and PM technologies the lower the fuel sulfur level the better the fuel economy of the vehicle.

As a result of these factors, we believe that it is appropriate to ensure that 15 ppm sulfur diesel fuel is available and are therefore capping in-use sulfur levels there.

4. Sulfur Sensitivity of Other Catalysts

Section 211(c)(2)(B) requires that, prior to adopting a fuel control based on a significant impairment to vehicle emissions control systems, EPA consider available scientific and economic data, including a cost benefit analysis comparing emissions control devices or systems

which are or will be in general use that require the proposed fuel control with such devices or systems which are or will be in general use that do not require the proposed fuel control. As described below, we conclude that the aftertreatment technology expected to be used to meet the final heavy-duty standards would be significantly impaired by operation on high sulfur diesel fuel. Our analysis of the available scientific and economic data can be found in the Preamble and RIA, including an analysis of the environmental benefits of the fuel control, an analysis of the costs and the technological feasibility of controlling sulfur to the levels finalized in the rule, and a cost effectiveness analysis of the final sulfur control and heavy-duty emissions standards. Under Section 211(c)(2)(B), EPA is also required to compare the costs and benefits of achieving the adopted vehicle emissions standards through emissions control systems that would not require the proposed control of sulfur, if any such systems are or will be in general use.

We have determined that there are not (and will not be in the foreseeable future) emission control devices available for general use on heavy-duty engines and vehicles that can meet the final heavy-duty emission standards and would not be significantly impaired by diesel fuel with high sulfur levels. NO_x and PM emissions can not be reduced anywhere near the magnitude contemplated by the standards promulgated today without the application of aftertreatment technology. While some improvement may yet be possible in engine out emissions, these improvements will not allow the engines to meet the set of emission standards promulgated today. As discussed in Sections III and IV of the Preamble and RIA, there are a number of aftertreatment technologies that are currently being developed for both NO_x and PM control with varying levels of effectiveness, sulfur sensitivity, and potential application to heavy-duty diesel vehicles.

As discussed in Sections III of the Preamble and RIA, all of the aftertreatment technologies that could be used to meet the PM or NO_x standards are significantly impaired by the sulfur in diesel fuel. For PM control, EPA is not aware of a PM aftertreatment technology that is capable of meeting the PM standard adopted today and that would not need the level of sulfur control adopted in this rule. In addition, the NO_x aftertreatment technologies evaluated by EPA all rely on the use of catalytic processes to increase the effectiveness of the device in reducing NO_x emissions. For example both NO_x adsorbers and compact SCR would rely on noble metals to oxidize NO to NO₂, to increase NO_x conversion efficiency at the lower exhaust temperatures found in diesel motor vehicle operation. This catalytic process, however, produces sulfate PM from the sulfur in the diesel fuel, and these NO_x aftertreatment devices need the level of sulfur control adopted in this rule in order for the vehicle to comply with the PM standard.

For NO_x control, both NO_x adsorbers and compact SCR are significantly impaired by sulfur in diesel fuel, and both technologies would need very large reductions in sulfur from current levels to meet the NO_x standard adopted today.

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In addition, compact SCR is not a technology that would be generally available by the model year 2007 time frame. Significant and widespread changes to the fuel distribution system infrastructure would have to be made and in place by then, and there is no practical expectation that this would occur, with or without the low sulfur standard adopted today. While it is feasible and practical to expect that compact SCR may have a role in specific controlled circumstances, such as certain centrally fueled fleets, it is not realistic at this time to expect that the fuel distribution system infrastructure changes needed for widespread and general use of compact SCR on heavy-duty diesel vehicles will be in place by the model year 2007 time frame. In addition, even if SCR were used to obtain the emission performance required by today's standards, it is not clear that the vehicles would continue to maintain that level of performance in-use. SCR technology requires continued replacement of the urea supply on the vehicle by the vehicle operator. Failure to do so would make the SCR system completely ineffective. While various options to encourage vehicle operators to maintain their urea supply have been suggested (e.g., electronically monitoring urea injection and reducing engine power if not), none provide reasonable assurance, and often raise other serious concerns such as the safety of vehicle operation. Finally, EPA believes that the requirement of a cost benefit analysis under section 211(c)(2)(B) is not aimed at evaluating emissions control technologies that would require significant additional or different EPA fuel control regulations before the technology could be considered generally available.

In sum, EPA believes that both PM and NO_x aftertreatment technologies require the level of sulfur control adopted today to meet the PM standards. There is no PM or NO_x emissions control device or system that would be in general use that does not need this level of sulfur control for purposes of controlling PM. EPA also believes that NO_x aftertreatment technologies either need the level of sulfur adopted today to be considered generally available for use to meet the NO_x standard, or need sulfur controls approximating those adopted and even with such sulfur control would not be considered generally available for use to meet the NO_x standard.

As described in Section III of the Preamble, EPA anticipates that all the diesel heavy-duty engine and vehicle technologies expected to be used to meet the final heavy-duty standards will require the use of low sulfur diesel fuel. If we do not control diesel sulfur to the finalized levels, we would not be able to set heavy-duty standards as stringent as those we are finalizing today. Moreover, vehicles already on the road would continue to emit at slightly higher levels than they would if operated on low sulfur fuel. Consequently, EPA concludes that the benefits that would be achieved through implementation of the vehicle and sulfur control programs cannot be achieved through the use of emission control technology that does not need the sulfur control adopted in this rule, and would be generally available to meet the emissions standards adopted in this rule .

This also means that if EPA were to adopt emissions control standards without controlling diesel sulfur content, the standards would be significantly less stringent than those finalized today based on what would be technologically feasible with current sulfur levels.

5. Effect of Diesel Sulfur Control on the Use of Other Fuels or Fuel Additives

Section 211(c)(2)(C) requires that, prior to prohibiting a fuel or fuel additive, EPA establish that such prohibition will not cause the use of another fuel or fuel additive “which will produce emissions which endanger the public health or welfare to the same or greater degree” than the prohibited fuel or additive. This finding is required by the Act only prior to prohibiting a fuel or additive, not prior to controlling a fuel or additive. Since EPA is not prohibiting sulfur in diesel fuel, but rather is controlling the levels of sulfur in diesel, this finding is not required prior to regulation. However, EPA does not believe that the finalized sulfur control will result in the use of any other fuel or additive that will produce emissions that will endanger public health or welfare to the same or greater degree as the emissions produced by diesel with uncontrolled sulfur levels.

Unlike in the case of unleaded gasoline in the past where lead served a primary function of providing the necessary octane for the vehicles to function properly, sulfur does not serve any useful function in diesel fuel. It is not added to diesel fuel, but comes naturally in the crude oil into which diesel fuel is processed. If it were not for the fact that it costs money to remove sulfur from diesel fuel, it would have been removed years ago to improve the maintenance and durability characteristics of diesel engines. EPA is unaware of any function of sulfur in diesel fuel that might have to be replaced once sulfur is removed, with the possible exception of lubricity characteristics of the fuel. As discussed in the Preamble, there is some evidence to suggest that as sulfur is removed from diesel fuel the natural lubricity characteristics of diesel fuel may be reduced. Depending on the crude oil and the manner in which desulfurization occurs some low sulfur diesel fuels can exhibit poor lubricity characteristics. To offset this concern lubricity additives are sometimes added to the diesel fuel. These additives, however, are already in common use today and EPA is unaware of any health hazards associated with the use of these additives in diesel fuel and would merely be used in larger fractions of the diesel fuel pool. We do not anticipate that their use would produce emissions which would reduce the large public health and welfare benefits that this rule would achieve.

EPA is unaware of any other additives that might be necessary to add to diesel fuel to offset the existence of sulfur in the fuel. EPA is also unaware of any additives that might need to be added to diesel fuel to offset any other changes to diesel fuel which might occur during the process of removing sulfur from diesel fuel.

APPENDIX B: Vehicle Miles Traveled by HDDE Class for Split by Pre-2007 and 2007+ Model Years (MY)

Calendar Year	LHDDE VMT [million miles]				MHDDE VMT [million miles]				HHDE VMT [million miles]				SUBTOTAL [million miles]				Urban Bus VMT [million miles]			Total VMT [million miles]				
	< 2007 MY	2007+ MY	Total	VMT% 2007+ MY	< 2007 MY	2007+ MY	Total	VMT% 2007+ MY	< 2007 MY	2007+ MY	Total	VMT% 2007+ MY	< 2007 MY	2007+ MY	Total	VMT% 2007+ MY	< 2007 MY	2007+ MY	Total	VMT% 2007+ MY	< 2007 MY	2007+ MY	Total	VMT% 2007+ MY
2005	47,678	0	47,678	0%	42,877	0	42,877	0%	166,573	0	166,573	0%	257,128	0	257,128	0%	3,189	0	3,189	0%	260,317	0	260,317	0%
2006	49,089	0	49,089	0%	44,145	0	44,145	0%	171,502	0	171,502	0%	264,736	0	264,736	0%	3,283	0	3,283	0%	268,019	0	268,019	0.0%
2007	45,046	5,454	50,500	10.8%	41,914	3,500	45,414	7.7%	161,793	14,638	176,431	8.3%	248,753	23,591	272,344	8.7%	3,243	134	3,378	4.0%	251,996	23,726	275,722	8.6%
2008	39,542	12,485	52,027	24.0%	37,025	9,762	46,787	20.9%	141,114	40,651	181,766	22.4%	217,682	62,898	280,580	22.4%	3,073	407	3,480	11.7%	220,755	63,305	284,059	22.3%
2009	34,682	18,872	53,554	35.2%	32,698	15,462	48,160	32.1%	122,939	64,162	187,101	34.3%	190,319	98,496	288,815	34.1%	2,896	686	3,582	19.1%	193,215	99,182	292,397	33.9%
2010	30,394	24,687	55,081	44.8%	28,870	20,664	49,534	41.7%	106,983	85,453	192,436	44.4%	166,246	130,804	297,050	44.0%	2,713	971	3,684	26.4%	168,958	131,776	300,734	43.8%
2011	26,612	29,996	56,608	53.0%	25,484	25,423	50,907	49.9%	92,990	104,780	197,770	53.0%	145,086	160,199	305,285	52.5%	2,523	1,263	3,786	33.4%	147,609	161,462	309,071	52.2%
2012	23,280	34,855	58,135	60.0%	22,489	29,791	52,280	57.0%	80,733	122,372	203,105	60.3%	126,502	187,018	313,520	59.7%	2,328	1,560	3,888	40.1%	128,830	188,578	317,409	59.4%
2013	20,345	39,317	59,662	65.9%	19,842	33,811	53,653	63.0%	70,006	138,435	208,440	66.4%	110,192	211,564	321,756	65.8%	2,128	1,863	3,990	46.7%	112,320	213,426	325,746	65.5%
2014	17,761	43,428	61,189	71.0%	17,500	37,526	55,026	68.2%	60,625	153,150	213,775	71.6%	95,886	234,105	329,991	70.9%	1,923	2,170	4,092	53.0%	97,808	236,275	334,083	70.7%
2015	15,487	47,229	62,716	75.3%	15,428	40,971	56,400	72.6%	52,429	166,681	219,110	76.1%	83,344	254,881	338,226	75.4%	1,713	2,482	4,195	59.2%	85,057	257,363	342,420	75.2%
2016	13,487	50,756	64,243	79.0%	13,594	44,178	57,773	76.5%	45,274	179,171	224,445	79.8%	72,355	274,106	346,461	79.1%	1,499	2,797	4,297	65.1%	73,854	276,903	350,758	78.9%
2017	11,728	54,043	65,770	82.2%	11,970	47,176	59,146	79.8%	39,031	190,749	229,780	83.0%	62,729	291,968	354,696	82.3%	1,283	3,116	4,399	70.8%	64,011	295,084	359,095	82.2%
2018	10,181	57,116	67,297	84.9%	10,531	49,989	60,519	82.6%	33,587	201,528	235,115	85.7%	54,299	308,633	362,931	85.0%	1,065	3,436	4,501	76.3%	55,363	312,069	367,432	84.9%
2019	8,821	60,003	68,824	87.2%	9,254	52,639	61,893	85.0%	28,844	211,606	240,450	88.0%	46,918	324,248	371,167	87.4%	848	3,755	4,603	81.6%	47,766	328,003	375,770	87.3%
2020	7,626	62,725	70,351	89.2%	8,119	55,147	63,266	87.2%	24,712	221,073	245,785	89.9%	40,457	338,945	379,402	89.3%	639	4,066	4,705	86.4%	41,096	343,011	384,107	89.3%
2021	6,575	65,303	71,878	90.9%	7,110	57,529	64,639	89.0%	21,115	230,005	251,120	91.6%	34,800	352,836	387,637	91.0%	451	4,356	4,807	90.6%	35,251	357,193	392,444	91.0%
2022	5,652	67,753	73,405	92.3%	6,212	59,801	66,012	90.6%	17,984	238,470	256,455	93.0%	29,848	366,024	395,872	92.5%	302	4,608	4,909	93.9%	30,149	370,632	400,782	92.5%
2023	4,840	70,092	74,932	93.5%	5,410	61,975	67,385	92.0%	15,261	246,529	261,790	94.2%	25,511	378,596	404,107	93.7%	210	4,802	5,012	95.8%	25,721	383,398	409,119	93.7%
2024	4,127	72,332	76,459	94.6%	4,694	64,065	68,759	93.2%	12,892	254,233	267,124	95.2%	21,712	390,630	412,342	94.7%	168	4,946	5,114	96.7%	21,880	395,576	417,456	94.8%
2025	3,499	74,487	77,986	95.5%	4,052	66,080	70,132	94.2%	10,832	261,628	272,459	96.0%	18,383	402,194	420,578	95.6%	134	5,082	5,216	97.4%	18,517	407,277	425,793	95.7%
2026	2,947	76,566	79,513	96.3%	3,477	68,028	71,505	95.1%	9,040	268,754	277,794	96.7%	15,465	413,348	428,813	96.4%	106	5,212	5,318	98.0%	15,570	418,560	434,131	96.4%
2027	2,462	78,578	81,040	97.0%	2,959	69,919	72,878	95.9%	7,483	275,647	283,129	97.4%	12,904	424,144	437,048	97.0%	84	5,337	5,420	98.5%	12,987	429,481	442,468	97.1%
2028	2,034	80,533	82,567	97.5%	2,493	71,759	74,252	96.6%	6,128	282,336	288,464	97.9%	10,655	434,628	445,283	97.6%	65	5,457	5,522	98.8%	10,721	440,085	450,805	97.6%
2029	1,658	82,436	84,094	98.0%	2,071	73,554	75,625	97.3%	4,950	288,849	293,799	98.3%	8,679	444,839	453,518	98.1%	51	5,574	5,624	99.1%	8,730	450,413	459,143	98.1%
2030	1,326	84,295	85,621	98.5%	1,689	75,309	76,998	97.8%	3,925	295,209	299,134	98.7%	6,940	454,813	461,754	98.5%	39	5,688	5,726	99.3%	6,979	460,501	467,480	98.5%
2031	1,023	86,125	87,148	98.8%	1,340	77,031	78,371	98.3%	3,009	301,460	304,469	99.0%	5,372	464,617	469,989	98.9%	26	5,803	5,829	99.6%	5,397	470,420	475,817	98.9%
2032	755	87,920	88,675	99.1%	1,022	78,722	79,745	98.7%	2,208	307,596	309,804	99.3%	3,986	474,238	478,224	99.2%	19	5,912	5,931	99.7%	4,005	480,150	484,155	99.2%
2033	526	89,677	90,202	99.4%	745	80,373	81,118	99.1%	1,565	313,574	315,139	99.5%	2,835	483,624	486,459	99.4%	13	6,020	6,033	99.8%	2,848	489,644	492,492	99.4%
2034	319	91,411	91,729	99.7%	472	82,019	82,491	99.4%	963	319,511	320,474	99.7%	1,753	492,941	494,694	99.6%	6	6,129	6,135	99.9%	1,760	499,069	500,829	99.6%
2035	138	93,118	93,256	99.9%	224	83,640	83,864	99.7%	444	325,364	325,809	99.9%	806	502,123	502,929	99.9%	3	6,234	6,237	99.9%	810	508,357	509,167	99.8%
2036	0	94,783	94,783	100%	0	85,237	85,237	100%	0	331,144	331,144	100%	0	511,165	511,165	100%	0	6,339	6,339	100%	0	517,504	517,504	100%