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Chapter 8

Transport

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This chapter has been allocated 40 template pages, currently it counts 69 pages (excluding this page and the bibliography), so it is 29 pages (!!) over target. Reviewers are kindly asked to indicate where the chapter could be shortened.

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Chapter 8: Transport

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Executive Summary

What is the current status of the transport sector?

Direct GHG emissions from transport of 7.0 Gt $CO_{2\text{-eq}}$ in 2010 constituted about one quarter of total energy-related CO_2 emissions. Global demands for passenger mobility and freight movements by road, rail, aviation, and waterborne transport systems are projected to continue to increase in the next few decades, particularly for freight and aviation, and mainly in non-OECD nations but starting from a low base. Based on continuing current rates of growth for passengers and freight, and without new GHG mitigation policies being implemented, emissions could double by 2035. The transport sector will therefore need to significantly contribute to global mitigation actions in order to avoid dangerous climate change [8.1, 8.9]. *[Robust evidence; high agreement]*

How difficult will it be to reduce GHG emissions from the transport sector?

Decarbonizing transport will be very challenging given the ever-increasing demand, the slow turnover of stock and infrastructure, the huge sunk costs in the present system, and the lack of progress in slowing growth of emissions to date, in spite of new technological developments and the various transport policies implemented since the AR4. The potential exists to make reductions of around 20-40% below projected levels of GHG emissions by 2050 through such actions as fuel switching, improving vehicle efficiencies, reducing demand for journeys, shifting modes, and developing appropriate infrastructure. Such deep reductions, which are beyond the levels found possible in the AR4, would enable the transport sector to contribute to a trajectory towards 450 ppm CO_2-eq atmospheric concentrations or below by 2100 [8.2, 8.3, 8.9]. *[Medium evidence; high agreement]*

What is new in the transport sector since the AR4?

- New policies have been introduced to reduce the carbon intensity of transport fuels [8.10]. Demand for biofuels is growing, including for aviation, but with concerns about the net climate effects of some biofuels. There is renewed interest in natural gas as a vehicle fuel [8.3] and increased deployment of technologies to reduce particulate matter and black carbon, particularly in OECD countries [8.2].
- More fuel economy and GHG vehicle performance standards have been implemented for light and heavy duty vehicles (LDVs and HDVs) coupled with significant engine and transmission technology developments. Mass-produced electric vehicles have entered the market [8.3, 8.10].
- ‘Slow-steaming’ of deep sea ships has become widespread practice and energy efficiency design standards have been established for new ships. Fuel economy standards have been introduced for trucks (8.10). Major logistics companies have opted to reduce the carbon intensity of their operations by 2015-2020.
- There is better comprehension of infrastructural developments and their impacts on behavioural choices, removal of barriers, and full life-cycle analyses (LCA) of GHG emissions. The need for careful interpretation of LCAs to avoid misunderstandings, including detailed examination of all assumptions used, is now better understood [8.3, 8.4, 8.8].
- Implementation of over 100 bus rapid transit systems, more provision of infrastructure for light-rail, and development of non-motorised transport options have been achieved with promotion of associated health benefits [8.4, 8.7].
- There has been more rapid LDV growth than projected in Asian countries with policies emerging to slow this growth. LDV ownership and annual passenger km per capita may be close to saturation in some OECD countries [8.9].
- Mobility access has been improved in developing countries [8.3, 8.9]. Local transport management policies have been widely implemented to reduce air pollution and traffic congestion [8.10].

For the transport sector to decarbonise and achieve its mitigation potential will require dramatic changes using a wide range of technologies, strategies and policies linked to fuel carbon intensity, energy intensity, infrastructure and activity. *[Robust evidence; high agreement]*
Emission reductions are feasible as a result of:

- reducing carbon intensity of fuels (CO_2-eq/MJ) by replacing oil products with natural gas, biofuels, electricity and hydrogen produced from low GHG sources. Natural gas produced using hydraulic fracturing processes, and some biofuels may not achieve this goal unless their life-cycle GHG emissions are properly managed [8.3].
- lowering energy intensity (MJ/km) by enhancing vehicle and system performance. This includes improvements in engines, power trains and vehicle designs; the use of new lightweight materials; better aerodynamics; and increasing the carrying capacity of freight vehicles. New propulsion systems coupled with low-carbon fuels are already playing a role, such as in the rapid deployment of two-wheel electric cycles [8.3].
- changing urban form and developing new infrastructure such as electrification. This can reduce the demand for conventional motorized transport modes relative to a reference case and enable uptake of low-C transport systems. Rural dwellers often have their choice of transport modes constrained, as do those living in very cold or hot climates. [8.4, 8.9]
- avoiding journeys such as by sourcing more localized products, restructuring logistics systems, and utilizing advancing information and communication technologies [8.3, 8.9, 8.10].

Short-term mitigation strategies can be cost-effective such as reducing emissions of short-lived climate forcing agents, fuel economy measures, supply chain improvements for freight, and behavioural change strategies. *[Medium evidence; medium agreement]*
Black carbon and aerosols can produce both positive and negative radiative forcings. Short-term reductions can be achieved through improved engine maintenance and retrofits. Methane and nitrous oxide vehicle tail-pipe emissions reductions are technically possible as are reducing high-altitude NOx emissions from aviation that effect ozone levels [8.2].

Seeking to change consumer behaviour by encouraging fuel economy, modal shifts and reducing travel demand can result in net societal benefits when all co-benefits are valued. This could dominate transport mitigation actions in the short-term in all regions by increasing the shares of low-carbon intensive modes such as cycling, walking and mass transit; improving road traffic flows; choosing rail or waterborne transport for freight movements; maximizing vehicle passenger occupancy and freight load factors; and reducing the length and number of journeys [8.3, 8.6].

Behavioural changes can be cost-effective but are difficult to predict and quantify since they are likely to vary significantly between regions and could be constrained by lack of social acceptance. Regulations and/or education such as when promoting the benefits of carbon-reducing measures to freight companies, may also be needed to give a value proposition [8.6, 8.10].

In the long-term (2050 and beyond), deep reductions in fuel carbon and energy intensities are feasible but could be offset by increased transport demand. Barriers to mitigation strategies will need to be overcome in order that GHG reductions, co-benefits and cost savings can all be achieved. *[Medium evidence; high agreement]*
Mitigation potential based on technological solutions could be constrained by relatively high costs (\$/t CO_2 avoided) in some countries. New transport patterns may need radical changes in land use, urban design, infrastructure development and R&D investment. Barriers to the deployment of improved technologies and practices can largely be overcome for those nations and cities willing to make low-carbon transport a priority [8.6, 8.8].

Decarbonizing aviation as a result of fuel carbon intensity reductions and improved aircraft efficiencies by 2050 could be largely offset due to high growth rates, especially in emerging economies. Competition from high-speed rail over middle distances, and better electronic communication systems, could partially offset aviation demand growth. The volume of international freight is expected to rise, but be accompanied by a range of carbon-reduction options (CO_2 /t-km) such as more efficient drive-trains, reduced vehicle tare weights, improved load capacity, fuel switching and reversing the recent freight modal shift from rail to road by using policy measures. Conventional and advanced biofuels (including "drop-in" fuels) could gain an increased share particularly for aircraft, HDVs and ships, but their mitigation potential depends on sustainable production and land use change issues [8.3] *[medium evidence; low agreement]*.

The interaction between land use policies and infrastructural developments can evolve over the medium- and long-terms to reduce the GHG intensity through transport-oriented urban development (Chapter 12). Oil price trends relative to average income, price instruments on GHG emissions, infrastructure provision, and regulations (such as pricing and limiting parking facilities) could shape future transport costs, demand growth, modal shares and urban forms at both the local and global scales but with regional differences [8.4, 8.9]. Impacts from climate change feedbacks are uncertain [8.5].

Optimal mitigation packages differ between regions and nations due to variations in local transport demand and existing infrastructure. *[Medium evidence; high agreement]*
National mitigation options vary with the stage of economic development, the fuels available, types and average ages of vehicle fleets, modal choices available and investment constraints [high agreement; medium evidence]. A long-term transformational pathway can meet multiple national objectives for both climate mitigation and sustainable development. Regions with existing and mature transport infrastructures in place may find it easier to improve energy intensity, and, to a lesser degree, reduce fuel carbon intensity, than to change travel patterns. Countries with rapidly developing infrastructures are more dynamic in terms of their ability to affect travel demands and modal choices, and hence may have greater flexibility when meeting their mitigation potential [8.9].

Separate transformative trajectories exist due to distinct regional differences between GHG emissions, mitigation options, mobility and accessibility objectives [8.9]. In non-OECD countries, improving transport accessibility is essential for sustainable economic development. In OECD countries, the 'off-shoring' of manufacturing to low-labour cost regions decouples freight-related emissions from GDP but can burden the exporting countries with higher volumes of freight traffic and emissions. The carbon intensity of logistics in emerging markets can be reduced over the next 10-20 years to offset much of this traffic growth.

Co-benefits resulting from climate change mitigation actions in the transport sector can significantly contribute to sustainable development. *[Robust evidence; high agreement]*
Examples of non-climate policies at all government levels have successfully reduced traffic congestion, travel costs and local air pollution as well as improved health, safety and energy security whilst lowering GHG emissions. Since rebound effects can undermine a particular policy, a balanced package of policies, including pricing initiatives and other behavioural approaches, can help drive the whole package [8.7, 8.10] *[medium evidence; medium agreement]*.

Knowledge gaps in the transport sector
There is a lack of comprehensive and consistent assessments of the worldwide potential and costs to mitigate GHG emissions from the transport sector. Better knowledge of consumer behaviour and the relationship between transport and lifestyle is needed, particularly how and when people will choose to use new types of low-carbon vehicles, other mobility services, and avoid making journeys.
How severely transport services and scheduled timetables could be impacted by climate change feedbacks, both positively and negatively, is unknown. The outcomes of climate change impacts on transport have not been determined, nor have the cost-effectiveness of carbon-reducing measures

in the freight sector and on possible rebound effects. Changes in transporting materials as a result of the decarbonization of other sectors and adaptation of the built environment are unknown.

8.1 Freight and passenger transport (land, air, sea and water)

Growth in the transport sector has continued unabated (other than a temporary decline due to the global financial crisis that started in 2008). The final energy consumption of the sector in 2010 rose to 99.5 EJ (27.4% share of the total) which was similar to industry (101.4 EJ) but lower than the building sector (121.8 EJ) (IEA, 2012a). Greenhouse gas (GHG) emissions from the transport sector have more than doubled since 1971, increasing at a faster rate than any other energy end-use sector to reach 7.0 $GtCO_{2\text{-eq}}$ in 2010 (Fig. 8.1.1). Over three quarters of this increase has come from road vehicles. As outlined in this chapter, reducing transport emissions will be a daunting task given the ever-increasing demand, the slow turnover of stock and infrastructure, the huge sunk costs in the present system, and the lack of progress in slowing growth of emissions to date, in spite of new technologies and the various transport policies implemented over the past few decades.

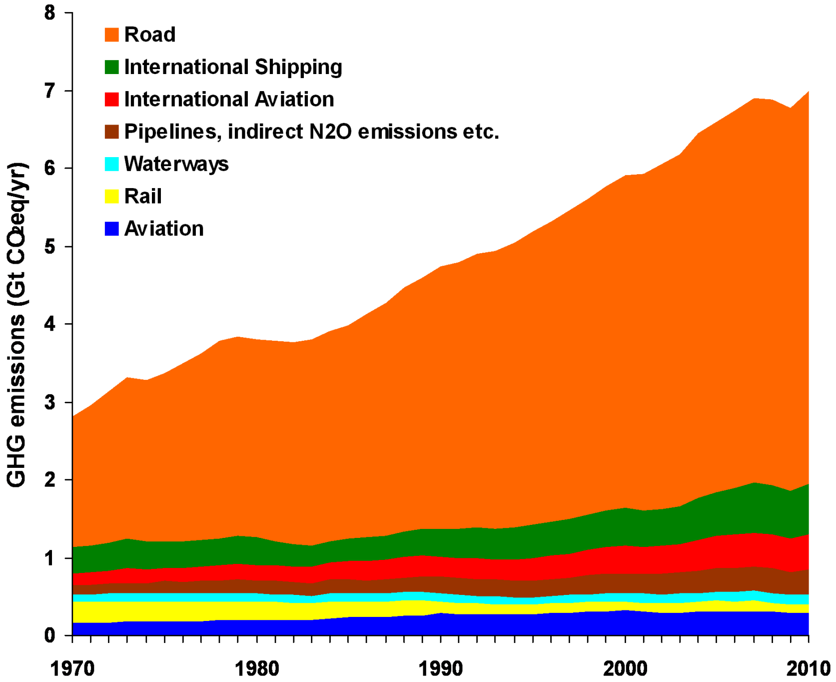


Figure 8.1.1. Global transport GHG emissions by sub-sector rose from 2.8 Gt $CO_{2\text{-eq}}$ in 1970 to 7.0 Gt $CO_{2\text{-eq}}$ in 2010 (IEA, 2012b; JRC/PBL, 2012).

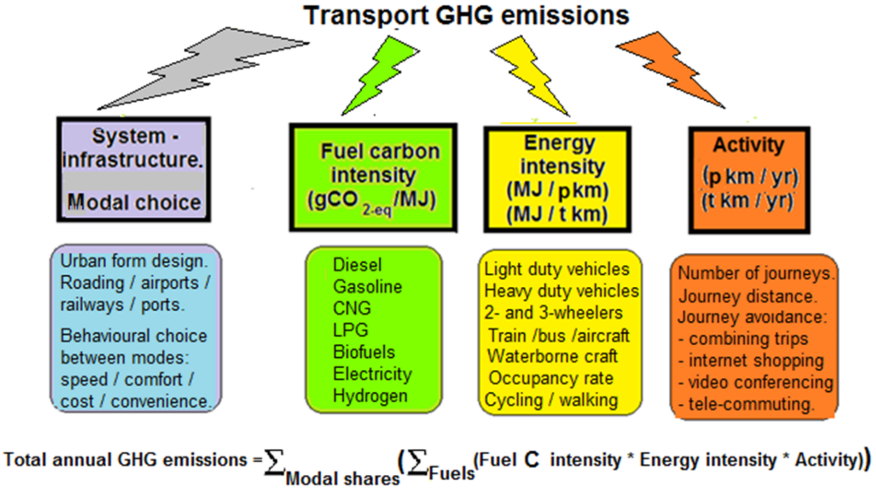
The IPCC 4th Assessment Report “Mitigation for Climate Change” (AR4) (IPCC, 2007) showed that:

- major technological advances and strong policies will be required to achieve a significant overall reduction in transport GHG emissions as demand was projected to continue to grow strongly;
- freight transport had grown more rapidly than passenger transport, mainly through the use of heavy duty road vehicles (HDVs) and shipping for international movements;
- local and regional conditions determine how shifts to less energy intensive modes, including public transport systems, promotion of non-motorised transport options, and development of related infrastructure, can contribute to GHG mitigation; and
- the mitigation potential by 2030 was 1.6 –2.5 Gt CO_2 for a carbon price of USD <100 /tCO_2 including 0.7–0.8 $GtCO_{2\text{-eq}}$ from energy efficiency options applied to light duty vehicles (LDVs) and around 0.28 $GtCO_{2\text{-eq}}$ for aviation.

New developments on the transport sector since the AR4 (as discussed in this chapter) include increased deployment of technologies to reduce particulate matter and black carbon, particularly in OECD countries; more fuel economy and GHG vehicle performance standards implemented; renewed interest in natural gas as a vehicle fuel due to the rapid increase in unconventional oil and gas extraction, especially in North America; an increase in the number of electric vehicles and bus rapid transport systems, but from a low base; more rapid LDV growth than projected in Asian countries with policies emerging to slow this growth including by investing in bus rapid transit and non-motorised transport systems; signs that LDV ownership and use (annual passenger km per capita) may have peaked in some OECD countries; increased awareness that mitigation strategies in urban areas, such as pedestrian and bicycle infrastructure, bus rapid transit system and light-rail, can simultaneously address broader sustainability concerns such as health, accessibility and safety; increased supporting policies and use of sustainably produced biofuels including for aviation; the maritime industry imposing GHG emission guidelines for shipping; and a greater overall understanding of infrastructural developments, mobility access, behavioural choice, and life-cycle emissions.

Direct GHG emissions for each mode of transport, although complex, can be decomposed[1] into:

- fuel carbon intensity (different transport fuels have varying carbon intensities);
- energy intensity (for each transport mode is directly related to vehicle efficiency); and
- activity (total passenger-km/yr or freight-km/yr) that has a positive feedback loop to the state of the economy and is, in part, influenced by behavioural issues (Fig. 8.1.2) (Bongardt et al., 2011; Creutzig, McGlynn, et al., 2011).



$$\text{Total annual GHG emissions} = \sum_{\text{Modal shares}} \left(\sum_{\text{Fuels}} (\text{Fuel C intensity} * \text{Energy intensity} * \text{Activity}) \right)$$

Figure 8.1.2. For each modal choice and fuel type option, direct GHG emissions can be decomposed into fuel carbon intensity (including non-CO_2 GHG emissions); energy intensity (specific energy input /p km or /t km for each vehicle option linked with occupancy rate); and activity (number and distance of passenger journeys or freight movements per year); which can be summated into total annual GHG emissions.

Notes: p km = passenger km; t km = tonne km; CNG = compressed natural gas; LPG = liquid petroleum gas. Indirect GHG emissions not shown - see section 8.1.2.

The various interactions between these emission factors (such as the deployment of electric vehicles impacting on travel behaviour), regional differences (such as limited modal choice in some developing countries) and avoiding journeys (Banister, 2011a) are included in this assessment. The co-benefits of improved air quality and health are discussed in section 8.2; technological and behavioural mitigation options in 8.3; infrastructure perspectives in 8.4 linked with Chapter 12; climate change feedback and adaptation in 8.5; costs and potentials in 8.6; co-benefits, risks and

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[1] This approach is based on the breakdown of transport GHG emissions into A (total Activity), S (modal Structure), I (modal energy Intensity) F (carbon content of Fuels); the so-called ASIF approach (Kamakaté and Schipper, 2009b).

social acceptability in 8.7; barriers and opportunities in 8.8; transformation pathways in 8.9 and policies in 8.10.

8.1.1 The context for transport of passengers and freight by land, air and water

Human welfare, food supplies, trade, and economic development all rely on the transport sector. The movement of an item of freight or a person from a starting location to a new place can involve one or more transport modes, each requiring energy inputs. As world population increases and standards of living improve, the demand for reliable, safe and affordable transport services continues to increase, with associated problems of local air pollution, noise pollution, increased dependence on oil products, traffic congestion, road accidents as well as higher GHG emissions, making a desirable transition to a low-carbon economy more challenging.

Direct emissions from the transport sector were about 13.5% of total anthropogenic GHG emissions in 2010 (Chapter 5) or 22% of total global energy-related CO_2 emissions (IEA, 2011a), but with wide regional variations (Fig. 8.1.3). Future GHG emissions are difficult to predict because oil and carbon prices are uncertain and the deployment rates of new and innovative options for vehicle designs, advanced biofuels, batteries, hydrogen fuel cells, infrastructure developments etc., are unknown (8.3). Modal shares for motorised travel vary widely between regions (Fig. 8.1.4) with OECD dominated by LDVs, Asia having a high and growing share of two and three wheel vehicles, and buses increasing shares in all regions (Fig. 8.1.4). Future modal shares are uncertain and will depend on income growth, being based on the options available, education and cultural developments, infrastructure investments and relative costs of different modes, and behavioural choices between cost, comfort, speed and convenience of journey. Hence scenario projections for future transport systems vary widely (8.9). Reducing demands for specific journeys or freight movements and encouraging modal shifts can be relatively low cost mitigation options, whereas other options have higher costs in terms of \$/t $CO_{2\text{-eq}}$ avoided (8.6).

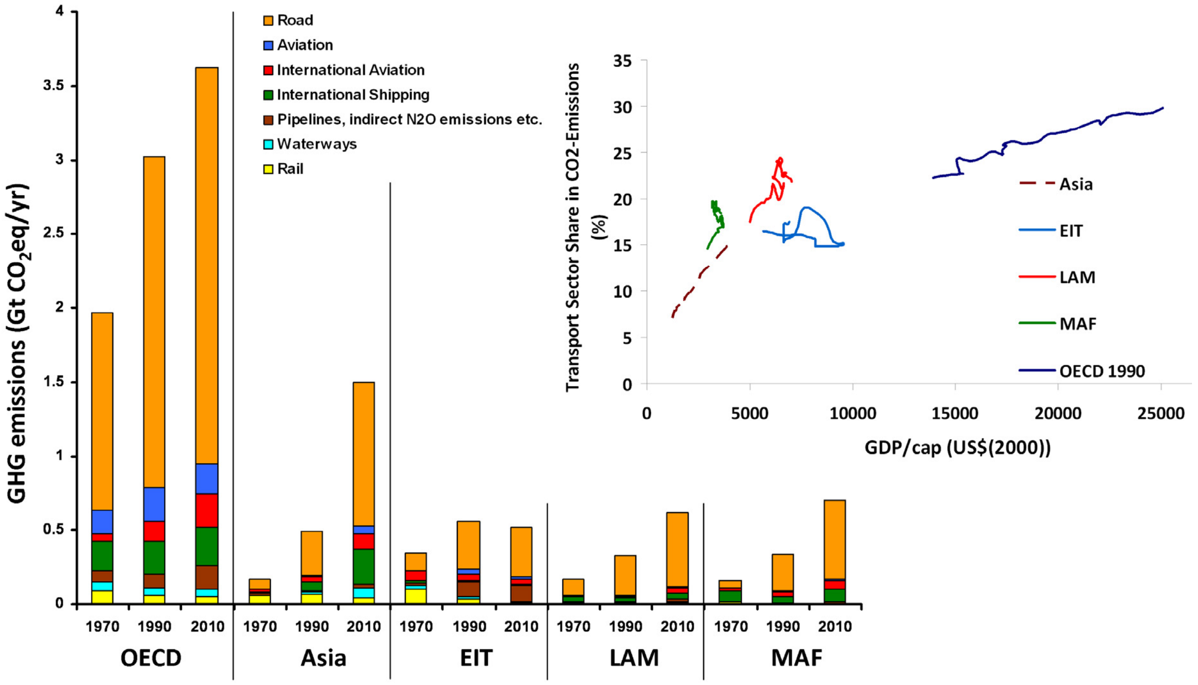

Figure 8.1.3. GHG emissions from transport sub-sectors by regions in 1970, 1990 and 2010. (IEA, 2012b; JRC/PBL, 2012). Inset shows that for transport, the relative share of total energy-related CO_2 emissions tended to increase during the period 1971-1998 due to structural changes as GDP / capita increased in a region, thus illustrating that transport emissions become more significant as countries become richer. (Adapted from (Schäfer et al., 2009; Bongardt et al., 2011).

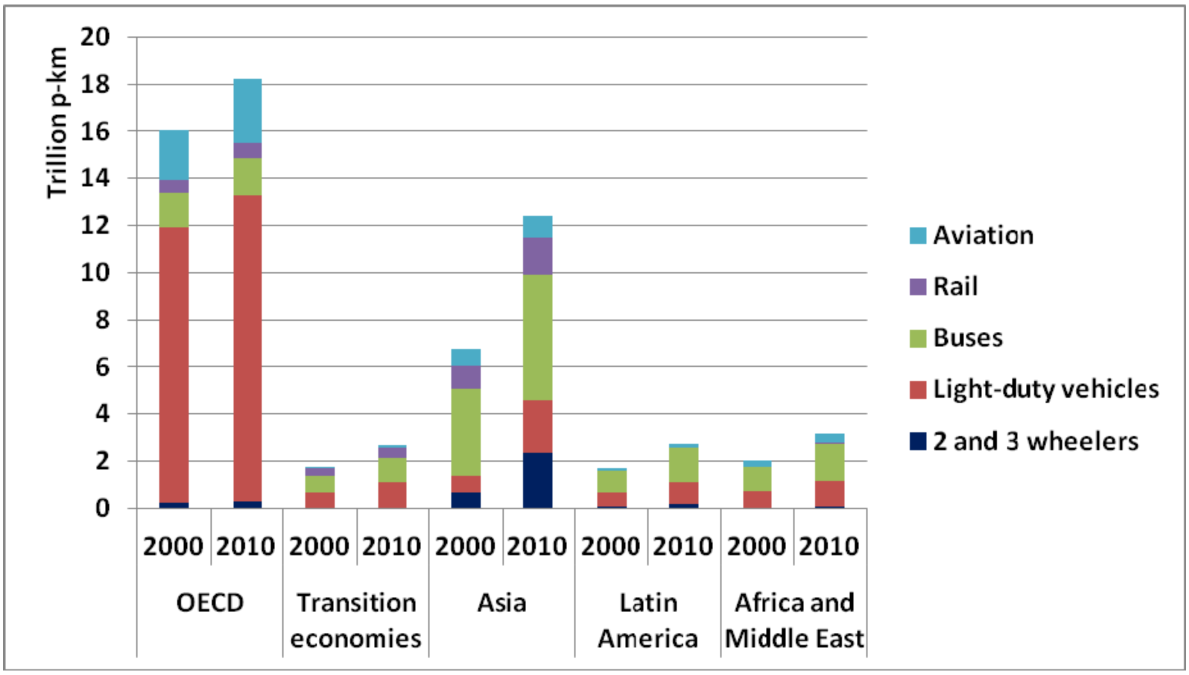

Figure 8.1.4 Modal shares of total passenger transport by region in 2000 and 2010 (IEA, 2012c)

Arising from the concept of sustainable development, "sustainable transport" decouples dependence on oil; constrains GHG emissions; encapsulates having accessibility to basic daily needs consistent with human and ecosystem health; and meets affordability, equity and efficiency requirements by providing fairness across and within generations (CST, 2002; ECMT, 2004; Bongardt et al., 2011; E C Environment, 2011). Variations between expected trends and co-benefits result from regional differences, such as. improved mobility in rural areas of least developed countries leading to better access to markets(Geurs and Van Wee, 2004; Zegras, 2011). Systemic goals for mobility, climate and energy security can help operationalize the more general sustainability principles (8.9.3) (Åkerman and Höjer, 2006; Kahn Ribeiro et al., 2012).

8.1.2 Energy demands and direct / indirect emissions for passengers and freight

Over 53% of global primary oil consumption in 2010 was used to meet 94% of total transport energy demand, with biofuels supplying approximately 2%, electricity 1%, and natural gas and other fuels 3% (IEA, 2012a) and Fig. 8.1.5). LDVs (both commercial and passenger) had a half share of total transport energy demand, with HDVs, plus agriculture and construction machinery, around one quarter (IEA, 2012c). Freight transport consumed almost 45% of total transport energy fuels.

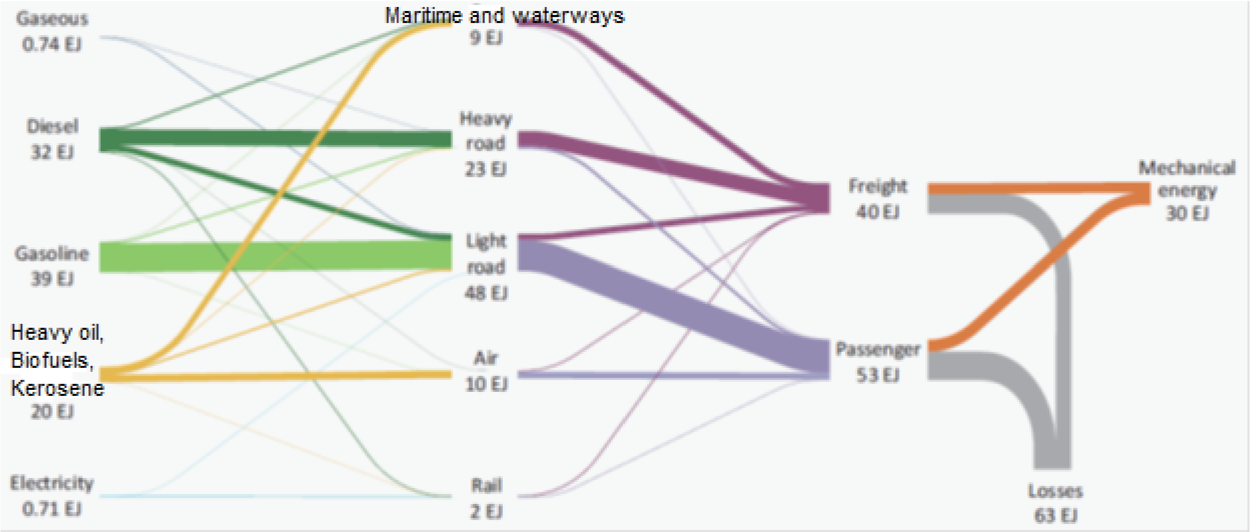

Figure 8.1.5 Final energy demand from fuels by transport sub-sectors in 2009 for freight and passengers and showing heat losses are around two thirds of total energy demand. Based on (ITF, 2005, 2011; IMO, 2009; ICAO, 2010a; IEA, 2010a, 2012d; UNCTAD, 2010; Newman and Kenworthy, 2011a; UIC, 2011a)

Approximately 65% of total aviation fuels in 2009 were consumed in OECD countries (ITF/OECD, 2010a; Graham et al., 2011). Of the remainder, China consumed 7%, other Asian countries 11%, and other non-OECD countries 17%. The tourism sector used air transport for 17% of all tourist trips in 2005 (ICAO, 2007a; UNWTO and UNEP, 2008), bus and train for about 34%, shipping a very small portion, and private car the rest (Peeters and Dubois, 2010). Air transport accounted for 43% of all tourism related CO_2 emissions, a share likely to increase to 53% by 2035 (Pratt et al., 2011). Freight movement is dominated by road transport, carrying around 5,100 bn t-km per year in 2009 (ITF, 2011), with rail moving around 350 bn t-km annually (UIC, 2011a) and air ~140 bn t-km (ICAO, 2010). Pipelines carry about 10% of total global freight t-km (ITF, 2005). International and coastal shipping transported around 7.8 bn t in 2009 (UNCTAD, 2010), consuming around 280 Mt of fuel in ships above 100 gross tonnage (GT) with a further 50-60 Mt used to transport 1-2 bn t of freight on inland waterways (IMO, 2009)[2]. Domestic shipping and fishing vessels possibly emitted an additional 176 Mt CO_2 /yr (IMO, 2009), although small boat data are particularly difficult to assess and therefore uncertain.

Direct vehicle CO_2 emissions per kilometre travelled vary with the fuel type, its source, the vehicle propulsion system, maximum vehicle carrying capacity and average loading. This leads to wide ranges (Fig. 8.1.6). Typical variations for freight movement range from ~2 gCO_2 /t-km for bulk shipping to ~1,700 gCO_2 /t-km for short-haul air, whereas passenger transport ranges from ~20-200 gCO_2 /p-km.

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[2] Note that some freight is carried by more than one mode during its journey from supplier to consumer.

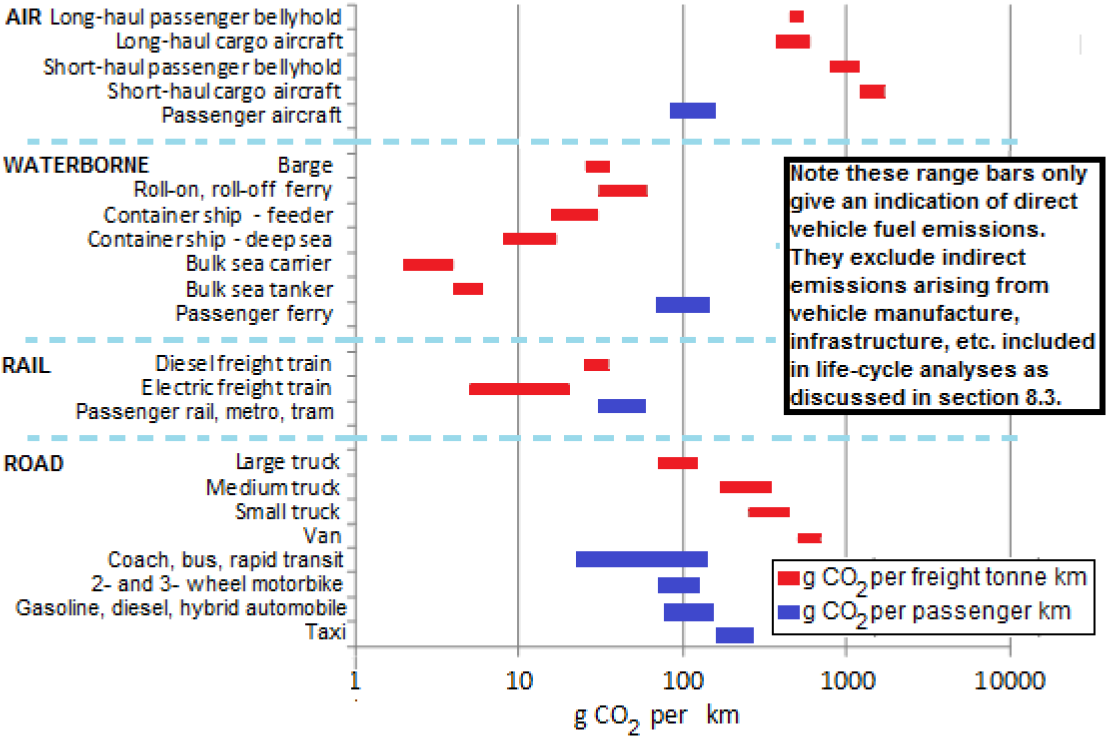


Figure 8.1.6 Typical ranges of direct CO_2 emissions per kilometre for passengers and per tonne-kilometre for freight, for the main transport modes when fuelled by fossil fuels including thermal electricity for rail. Sources: (ADEME, 2007; US DoT, 2010; Der Boer et al., 2011; NTM, 2012; WBCSD, 2012)

Direct emissions data for specific transport modes provide an incomplete assessment of their total GHG emissions output. Indirect GHG emissions should also be included using life cycle analyses (LCA) [8.3 and Annex 2]. These emissions emanate from upstream “well-to-tank” activities, the manufacture, maintenance and disposal / recycling of vehicles (Chapter 10), and from the construction and maintenance of transport networks and infrastructure (8.4 and Chapter 12). Long-lived methane and nitrous oxide emissions (Fuglestvedt et al., 2008; Takeshita, 2012b), together with F-gases (fluorinated halocarbons) leaked from vehicle air conditioners and refrigerated movement of perishable foods (IMO, 2009), are also responsible for about 5% of transport GHG emissions. However, the data are uncertain. Short-lived climate forcers such as black carbon (of which 20% arises from transport), stratospheric and tropospheric ozone, and other aerosols (8.2) are also emitted by transport activities (Bond et al., 2004).

8.2 New developments in emission trends and drivers

Assessments of transport CO_2 emissions require a comprehensive regional understanding of trends, and overall macroscopic observations sufficient to develop pathways for reducing emissions. Transport of goods and people vary considerably across nations in terms of the shares of emissions associated with the transport sector and direct transport CO_2 emissions per capita (IEA, 2009; Millard-Ball and Schipper, 2011; Salter and Newman, 2011). Transport’s share of total GHG emissions ranges from 30% in rich economies to less than 5% in less affluent economies, mirroring the structural transition to industrial and service sectors (Schäfer et al., 2009; Bongardt et al., 2011). A broad range of indicators are used such as travel activity, occupancy rates and fuel consumption per capita to measure sustainable mobility performance and assess progress (WBCSD, 2004; (Hall, 2006) (Dalkmann and Brannigan, 2007) (Joumard and Gudmundsson, 2010) (Kane, 2010) (Litman, 2007) (Ramani et al., 2011). Regionally, petroleum product consumption for all transport demands in

2009 ranged from 52 GJ /capita in North America to less than 4 GJ /capita in Africa and India where transport for many poor people is limited to walking and cycling. Likewise, residents and businesses of some cities in the USA annually consume over 100 GJ/capita whereas those in many Indian and Chinese cities use less than 2 GJ /capita (Newman and Kenworthy, 2011b).

FAQ 8.1: How much does the transport sector contribute to GHG emissions and how is this changing?

The aviation, waterborne, rail and road transport subsectors for moving both freight and passengers currently constitute about one quarter of total global energy-related CO_2 emissions and also significantly contribute to black carbon and aerosol emissions. Greenhouse gas emissions from the transport sector more than doubled since 1971, to reach 6.8 $GtCO_{2\text{-eq}}$ by 2010, with over three quarters of this increase coming from road vehicles.

Transport demand is expected to continue to increase, in particular in non-OECD countries. This rapid increase will be in part motivated by a fast demand growth in non-OECD countries that are starting at a very low base, but also by the strong growth of freight and air travelled kilometres worldwide. This is due to factors like the steady increase of income per capita, improved mobility access, improved transport infrastructure and rapid growth in light-duty-vehicle (LDV) ownership and use in developing and emerging countries, but also of economic wealth all over the world. If no mitigation options are implemented, the transport sector’s GHG emissions could double by 2035 at continued current rates of growth, which may see an increase of transport’s share of global energy-related CO_2 emissions.

8.2.2 CO_2 emissions

From 2000 to 2006, transport CO_2 emissions from non-OECD nations grew at a rate of 4.3% per year as compared to 1.2% per year from OECD nations (IEA, 2009). The annual growth rates varied considerably across transport sub-sectors. For OECD countries, the largest annual growth over this period was in international shipping (2.5%), followed by rail (2.3%), road (1.4%) and international aviation (1.2%). Domestic waterways and aviation decreased by 1.0% and 0.3% respectively (IEA, 2009). For non-OECD countries, the largest annual growth was also in international shipping (5.4%), followed by international aviation (4.7%), road (4.2%), domestic waterways (4.0%), domestic aviation (3.0%), and rail (2.3%), with no sectors having negative growth (IEA, 2009). There is some evidence that passenger LDV travel in OECD countries has begun to flatten or even decline since 2000 (IEA, 2009a, 2012d; Meyer et al., 2012), suggesting “peak” travel may be occurring and raising the possibility of a significant turning point in transport (Goodwin, 2012; Millard-Ball and Schipper, 2011; Schipper, 2011). This is not expected to off-set growth in developing countries (8.2.1.2).

8.2.2.1 Drivers

The major drivers that affect transport trends are travel time budgets; costs and prices; and economic, social, and cultural factors (OECD, 2006; ITF, 2011). From an urban planning perspective, the spatial structure and existing systems for moving people and freight impact on the demand for transport and modal choice (Anas et al., 1998). There is increasing appreciation that changing urban form through planning and development can play a large role in the mitigation of transport GHG emissions. Costs and prices are factors that shape transport systems with the high costs of infrastructure requiring significant capital investment (8.4). These investments can be managed in a manner that shapes or responds to existing trends in urban form. Although there is no clear consensus within urban planning on the best approaches from the climate mitigation perspective, urban development can be used as a tool to reduce the demand for transport and shift the modal distribution (Fig. 8.1.4).

***Travel time budget*.** Transport helps to determine the urban and regional economy through the time taken to move people and goods around. Travel time budgets have been shaping cities and causing competitive advantage in regional freight movements for as long as human settlements have existed. Urban travel time budgets averaging around 1 hour per capita per day for the commute between work and home, or 1.1 – 1.3 hours per traveller per day (Zahavi and Talvitie, 1980; van Wee et al., 2006) have been found to occur in all cities where data is available, including in both developed and developing economies (Marchetti, 1994; Mokhtarian and Chen, 2004). Infrastructure for walking, LDVs, or mass transit is usually designed so that destinations can be reached in half an hour on average. Land use is adapted to enable this average time to be maintained (Newman and Kenworthy, 1999). Travel time budgets are usually fixed and tied to both travel and time costs (Noland, 2001; Cervero, 2001; Noland and Lem, 2002). Cities vary in the proportion of people using different transport modes and have adapted land uses to fit these modes at speeds of around 5 km/hr for walking, 20-30 km/hr for mass transit and 40-50 km/hr for LDVs, the latter subject to great variability. New road infrastructure construction has reduced car travel time dramatically worldwide, and hence encouraged an increase in the use of road transport. Travel times can be increased by traffic congestion, transit congestion or walking/bicycling congestion, with the problem being eased by infrastructure development, but with the land use quickly adapting so that a similar travel time eventually resumes (Mokhtarian and Chen, 2004). Regional freight movements do not have the same fixed time demand but are based more on the need to remain competitive and are limited to a small proportion of the total costs of the goods (Schiller et al. 2010).

***Costs and prices*.** The relative decline of transport costs as a share of personal income has been the major driver of increased transport demand in OECD countries in the last century and more recently in non-OECD countries. The price of fuel is a major factor in determining the level of LDV use versus public transport, cycling or walking (Hughes et al., 2006). Average pre-tax global gasoline and diesel fuel prices increased by more than a factor of three from 2001 to 2008 after a decade of stability (BP, 2012). Then from 2008 to 2012, fuel prices fluctuated considerably and there are no clear trends to predict future fuel prices given unknown economic factors, the uptake rate of alternative fuels, and climate mitigation policies (Nezhad, 2009).

In developed countries, fuel prices at the pump have partly contributed to a levelling or potentially decreasing usage of LDVs (Newman and Kenworthy, 2011b). Transport fuel prices, heavily influenced by taxes, also impact on the competition between road and rail freight. The costs of operating HDVs increase dramatically when fuel costs go up (Dinwoodie, 2006). Increased fuel costs have also promulgated the designs of more fuel efficient engines and vehicle designs (8.3) (IEA, 2009). Due to the average life of aircraft and marine engines being two to three decades, fleet turnover is slower than for road vehicles and small boats. However, given that fuel costs are a relatively high share of total aviation or boating costs, improving fuel efficiency makes good economic sense (IEA, 2009).

Economic, social and cultural drivers. Population growth and changes in demographics are major drivers for transport demand and model shift. Structural change in many national economies has led to increased specialization of jobs, a more gender-diversified workforce, and more and longer commutes (Levinson, 1999). Additionally, as shopping becomes more concentrated (allowing for more products in one location), travel distance to the shops also tends to increase (Weltevreden, 2007). Similarly, economic globalisation, associated with global specialization, has increased the volume of global freight movement (Henstra et al., 2007).

At the household level disposable income is a major driver in personal access and mobility choices. Once a motorized vehicle becomes affordable even in relatively poor households in many developed countries, then it becomes a major item of individual consumption, second to expenditure on housing, and one that has so far proved increasingly popular with each new generation (Trubka et al., 2010a; b; c). Motorized two, three and four-wheelers can provide fast, convenient and flexible transport services for their owners. Owning and driving a motorbike or car provides symbolic and affective functions that significantly contribute to the positive utility of driving (Mokhtarian and

Salomon, 2001; Steg, 2005; Urry, 2007). Different social groups value these aspects differently (Steg, 2005). In some societies, obtaining a license and driving a LDV has become a sign of status and created a basis of sociability and networking through the various sign-values of speed, safety, sexual success, career achievement, freedom, family, masculinity and emancipation of women (Miller, 2001; Carrabine and Longhurst, 2002; Sheller, 2004; Urry, 2007; Bamberg et al., 2011). Affective motives, such as the power and sensation feeling of superiority associated with owning and using a car, influence travel behaviour, for example breaking speed limits, with consequences on traffic safety, energy consumption, noise and emissions (Bamberg et al., 2011). In short, modal choices are sometimes driven by social factors that are above and beyond the usual drivers of time, cost and price. Some urban dwellers avoid using mass transit or walking due to safety and security issues. Conversely, there is some evidence of younger people choosing mass transit over LDVs (Parkany et al., 2004). Lifestyle and behavioural factors in transport are important for any assessment of potential change to low carbon options. Additional research is needed to assess the willingness of people to change (Ashton-Graham, 2008). Tourism is expected to be another driver for all modes of transport (8.1, 10.3.3) and significant disruptive technologies such as driverless cars and consumer based manufacturing could have important impacts on future transport demands that are difficult to predict.

8.2.2.2 Trends

As economies shift from agriculture to industry to service, the absolute emissions of transport (Fig. 8.1.1) and also the share of total GHG emissions by the transport sector have risen considerably (Chapter 5). As people have become richer, absolute CO_2 emissions from transport have historically risen, as well as their relative share of per capita total emissions (Schäfer et al., 2009). As international trade expands and the demand for transport of goods and people increases worldwide, the cost of transport relative to disposable income continues to decrease (Bliijenberg, 2012). In emerging economies, increased demand for transport is being met by expansion of bus and rail public transport together with expansion of roadways and increased LDV ownership. Total LDV ownership is expected to double in the next few decades (IEA, 2009a) from the current level of around 1 billion (Sousanis, 2011). Two-thirds of this growth is expected in non-OECD countries. However, even in this case, per capita ownership level of LDVs in non OECD countries will remain much lower than in OECD countries.

Air transport demand continues to increase in the US, Canada and Australia but has declined in Europe and Japan possibly due to improvements in high-speed rail (Millard-Ball and Schipper, 2011). In non-OECD nations, air transport demand continues to rise even with the simultaneous development of high-speed rail in some countries.

Although there is significant regional diversity on the modal distribution of urban and inter-urban transport, there is limited evidence that changes in carbon intensity, energy intensity and activity have made significant constraints on GHG emissions growth (8.6). Recent transport trends suggest that current economic, social, or cultural changes alone will not be sufficient to mitigate global increases in atmospheric CO_2 concentrations. Stringent policy instruments, incentives, or other interventions will be needed to reduce global transport CO_2 emissions (IEA, 2009a).

8.2.3 Non-CO_2 greenhouse gas emissions, black carbon and aerosols

The transport sector emits a number of non-CO_2 pollutants that also impact on the climate. These include methane, nitrogen oxides, sulphur dioxide, volatile organic compounds, black carbon, non-adsorbing aerosols and F-gases (Unger et al., 2010). Methane emissions are largely associated with leakage from the production and filling of natural gas powered vehicles. Volatile organic compounds and nitrous oxide are emitted from vehicle internal combustion engines (ICE). Total transport-related F-gas emissions (from air conditioning and refrigeration) are around 350 Mt $CO_{2\text{-eq}}$ per year (EPA, 2006). All of these pollutants are important to global climate change. However, some can have much larger regional climate impacts.

Black carbon and non-absorbing aerosols have short lifetimes in the atmosphere of only days to weeks, but can have significant direct and indirect radiative forcing effects (Bond et al., 2013) . In North America, South America and Europe, over half of black carbon emissions are due to the use of diesel and heavier distillate fuels in transport (Bond et al., 2013). Black carbon emissions are also significant in parts of Asia and elsewhere from biomass and coal combustion but the relative contribution from transport is expected to grow in the future (Bond et al., 2013). There is strong evidence that reducing black carbon emissions from HDVs, off-road vehicles and shipping would present an important short term strategy to mitigate atmospheric concentrations of pollutants with positive radiative forcing.

Transport is also a significant contributor of primary aerosols that do not absorb light, and gases that undergo chemical reactions to produce secondary aerosols. Primary and secondary organic aerosols, secondary sulphate aerosols formed from sulphur dioxide emissions, and secondary nitrate aerosols from nitrogen oxide emissions from ships, aircraft and road vehicles can have strong local regional cooling impacts (IPCC, AR5 Working Group I). Contrails from aircraft and emissions from ships impact on the marine boundary layer and the troposphere (Fuglestvedt et al., 2009a; Lee et al., 2010).

Relative contributions of different pollutants to radiative forcing in 2020 have been compared with continuous constant emissions from 2000 (Unger et al., 2010). Although this study did not provide a realistic projection for future emissions scenarios, it did offer a qualitative comparison of short- and long-term impacts of different pollutants. Relative to CO_2, the major short-term impacts stem from black carbon, indirect effects of aerosols and ozone from land surface vehicle, and aerosols and methane emissions are associated with ship and aircraft. Due to the longer atmospheric lifetime of CO_2, these relative impacts will be greatly reduced when integrated from the present time to 2100 (Unger et al., 2010).

Although emissions of non-CO_2 GHGs and aerosols are impacted by reducing carbon intensity, improving energy intensity, modal choice and transport activity, the emissions of non-CO_2 gases can be significantly reduced by technologies that prevent their formation or lead to the destruction of these pollutants using after-treatments. Some of these emissions control devices, such as diesel particulate filters (DPF) and selective catalytic reduction (SCR), have fuel efficiency penalties (Tourlonias and Koltsakis, 2011). These can lead to an increase in transport CO_2 emissions, but the human health benefits from emissions reductions and the co-benefits of climate change mitigation through black carbon reductions need to be better assessed (Woodcock, Edwards, Tonne, Armstrong, Ashiru, Banister, Beevers, Chalabi, Chowdhury, and Cohen, 2009).

Short-term mitigation strategies that focus on black carbon, contrails from aircraft, and ship emissions can play an important role in developing pathways for climate mitigation (Shindell et al., 2012). Policies are already in place for reducing emissions of F-gases, which are expected to continue to decrease with time (Prinn et al., 2000).

8.2.3.1 Drivers and trends

Non-CO_2 emissions from road and shipping activity have historically been constrained by local air quality regulations that seek to protect human health and welfare by reducing ozone, particulate matter, sulphur dioxide and toxic components or aerosols, including vanadium, nickel, and polycyclic aromatic hydrocarbons (Verma et al. 2011). Due to the importance of regional climate change in the context of mitigation, there has been growing awareness of the climate impact of these emissions. More efforts are being directed at potential programmes to accelerate control measures to reduce emissions of black carbon, ozone precursors, aerosols and aerosol precursors (Lin and Lin, 2006)

Due to strict regulatory requirements, non-CO_2 GHGs and aerosol emissions from road vehicles continue to decrease per unit of travel in many regions due to efforts to protect human health from air pollution. The implementation of these controls could potentially be accelerated as a driver to mitigate climate change (Oxley et al., 2012). Additional pressures to reduce aviation emissions and national and international programmes to reduce aerosol and sulphate emissions from shipping are being implemented (EC, 1999).

8.3 Mitigation technology options, practices and behavioural aspects

Technological improvements and new technology-related practices can make substantial contributions to climate change mitigation in the transport sector. This section focuses on energy intensity reduction technology options for light duty vehicles (LDVs), heavy duty vehicles (HDVs), ships, trains and aircraft and fuel carbon intensity reduction options related to the use of natural gas, electricity, hydrogen and biofuels. It also addresses some technology-related behavioural aspects such as the uptake and use of new technologies and rebound effects associated with them. Urban form and modal shift options, which constitute another major component of climate change mitigation in transport, are discussed in 8.4.

FAQ 8.2: What are the main mitigation options in the Transport Sector and what is the potential for reducing GHG emissions?

Transport is a key enabler of economic activity and social connectivity and its carbon emission are driven by the overall travel demand, mode structure, fuel intensity of each mode and vehicle, and the carbon content of the fuel. As such, three families of mitigation alternatives exist: avoidance of unnecessary travel, for example through shortening distances in compact cities, shifting transport to more efficient modes, such as public transport, walking and cycling, improving efficiency of the vehicles and optimising their operations, and shifting to lower carbon fuels and energy carriers, such as sustainable biofuels and electric vehicles relying on electricity generated by renewables. These mitigation options apply for both freight and passenger transport, but may not be equally available for all transport modes (land, air and waterborne). Policy options to utilise these mitigation options include fiscal incentives and disincentives, e.g. fuel and vehicle taxes, standards on vehicle efficiency and emissions, infrastructure investments in public transport, waking and cycling and integrated urban and transport planning.

The potential of transport mitigation options, ranges from 40-70% efficiency improvement for LDVs and 30-50% efficiency improvement by 2035 for HDVs, up to 50% efficiency improvement of new planes by 2035, 5-30% efficiency gains for new ships and various other operational and modal sift measures (see Table 8.6.1). The actual potential of various mitigation options is influenced by factors such as economic development, structure of the vehicle fleet, fuels available and existing infrastructure and may vary from region to region and across transport modes.

8.3.2 Reducing energy intensity - incremental vehicle technologies

Recent advances in LDVs in response to strong regulatory efforts in Japan, Europe and the US have demonstrated that there is substantial potential for improving internal combustion engines (ICEs) for road vehicles with both conventional and hybrid drive-trains. Recent estimates suggest substantial additional, unrealised potentials exist with up to 50% improvements in vehicle fuel economy (MJ/km) compared to similar-sized, typical 2007-2010 vehicles (Bandivadekar, 2008; Greene and Plotkin, 2011). Similar or slightly lower potentials exist for trucks, ships and aircraft.

8.3.2.1 LDV drive-trains

As of 2011, leading-edge LDVs in Europe, Japan and elsewhere have drive-trains with down-sized direct injection gasoline or diesel engines (many with turbochargers) and a range of sophisticated components, coupled with automated manual or automatic transmissions with 6 or more speeds (SAE International, 2011). Drive-train redesigns of average vehicles to bring them up to this level could yield reductions in fuel consumption and GHG emissions of 25% or more (NRC, 2011a). In

EU27, average CO2 emissions of new model LDVs in 2010 were 140 g CO_2/km, while some models achieved below 100 g CO_2/km, partly from advanced drive-trains (EEA, 2011).

Hybrid drive-trains (ICE and electric motor with battery storage) can provide reductions up to 35% compared to similar non-hybridised vehicles today (IEA, 2012d). Hybrid cars have become a mainstream technology but only achieved a few share of annual sales in most countries over the last decade with the exception of Japan where 2 million hybrid cars have been sold by 2011 (IEA, 2012d).

Over the next two decades, there is substantial potential for further advances in drive-train technology, design and operation, including deploying a range of advanced incremental technologies (NRC, 2011a).

8.3.2.2 LDV load reduction

Lower LDV fuel consumption can be achieved by reducing all the loads that the vehicle must overcome, from aerodynamic forces, auxiliary components (including lighting and air conditioners), and losses from rolling resistance. Weight reduction is critical: if vehicle performance is held constant, reducing vehicle weight by 10% would allow a fuel economy improvement of about 7% (EEA, 2006). There are three basic approaches to reduce weight (NRC, 2011a): 1) Incremental redesign by removing material from the structural body; 2) Substitution of steel by aluminium and carbon fibre; and 3) Fundamental redesign of the vehicle structure.

Other changes that reduce loads include more efficient air conditioners, heaters, and lighting; improved aerodynamics, and lower rolling-resistance tyres. Together, these non-drivetrain changes offer potential reductions of up to 25% in fuel consumption. Combined with improved engines and drive-train systems, overall LDV fuel consumption per kilometre for new ICE-powered vehicles could be reduced by up to half by 2035 compared to 2005 (Bandivadekar, 2008; NRC, 2009). This is roughly consistent with the Global Fuel Economy Initiative target of a 50% reduction in global average new LDV fuel use per kilometre in 2030 compared to 2005 (Eads, 2010).

Overall fuel economy improvements by the LDV fleet will depend on multiple factors, including the extent to which automakers focus on efficiency and CO_2 emissions versus vehicle performance and other features; the size distribution of vehicles chosen by consumers; and changing preference to purchase the most efficient vehicles. Policies can help to encourage production and sales of the most efficient models (8.10). Actual in-use fuel economy will also depend on a range of factors, such as driving conditions (congestion, highway speed limits, etc.) driving practices, and vehicle maintenance (8.3.5).

8.3.2.3 Medium and heavy-duty vehicles

Most modern medium and HDVs already have efficient diesel engines (up to 45% thermal efficiency), and long-haul trucks often have streamlined spoilers on their cabs to reduce drag, particularly in OECD countries. Aerodynamic drag can also be reduced using other modifications offering up to 10% reduction in fuel consumption (TIAX, 2009; NRC, 2010a; AEA, 2011) . In non-OECD countries, many older trucks with relatively inefficient (and highly polluting) engines are common. Truck modernization along with better engine, tyre and vehicle maintenance, can significantly improve fuel economy in many cases.

Medium and HDVs in the US can achieve a reduction in energy intensity of 30-50% by 2020 by using a range of technology and operational improvements (NRC, 2010a) Few similar estimates are available in non-OECD countries but most technologies eventually will be applicable for HDVs around the world.

Expanding the carrying capacity of HDVs, in terms of both volume and weight, can yield significant net reductions in the energy intensity of trucks, so long as the additional capacity is well utilised. A comparison of the performance of 18 longer and heavier HDVs in nine countries (ITF/OECD, 2010b) concluded that higher capacity vehicles can significantly reduce CO_2 emissions per tkm without adverse impacts. The use of long combination vehicles rather than single trailer vehicles has been shown to cut direct GHG emissions by up to 32% (Woodrooffe and Ash, 2001).

Trucks and buses that operate largely in urban areas with a lot of stop-and-go travel can achieve substantial benefits from using electric hybrid or hydraulic hybrid drive-trains. Typically a 20-30% reduction in fuel consumption can be achieved via hybridisation (Chandler et al., 2006; AEA, 2011).

8.3.2.4 Rail

Technologies for rail energy efficiency improvements include multiple drive-train efficiency improvement and load-reduction measures. In Japan, the high-speed "Shinkansen" train has achieved 40% reduction of energy consumption by optimizing the length and shape of the lead nose, reducing weight and using efficient power electronics (UIC, 2011a). In US, the use of regenerative braking systems has enabled the rail company Amtrak to reduce energy consumption by 8% (UIC, 2011a).

Major efficiency improvements in China's rail system include the shift from non-electric rail to electric rail and to high-speed rail (which although more energy intensive than conventional rail per passenger kilometre, typically has high occupancy and other modal shift effects. These and other efficiency measures have contributed to a reduction in CO_2 emission intensity of China's rail system by 87% from 1975 to 2007 (He et al., 2010).

The European rail sector could improve its energy efficiency by 6% by 2020 against a 2005 base line through a combination of operational and technological improvements (UIC, 2011a). European rail operators have set targets of 30% improvements by 2020, 50% by 2030 and carbon-free travel by 2050 (UIC, 2011a) based on full electrification of the system along with full decarbonisation of the electric sector. However, since railway systems are already relatively carbon efficient, rail's biggest CO_2 reduction may come from a significant modal shift from road to rail – though the benefits will depend heavily on the types of freight or passenger travel shifted and the load factors involved (IEA, 2009).

8.3.2.5 Waterborne transport

Shipping is a comparatively efficient mode of freight and passenger transport, although size and load factor are important determinants for specific ships. Demand is increasing rapidly and GHG emissions from ships are projected to increase by 50% or more between 2008 and 2050 (IEA, 2010b). The International Maritime Organisation (IMO) has devised an Engine Efficiency Design Index for ships and set minimum standards for new vessels registered after 2015 and 2020. This is supplemented by a voluntary Ship Energy Efficiency Management Plan for new and existing ships (8.10).

Several studies have reviewed the broad range of carbon abatement options available (AEA, 2007; IEA, 2009a; IMO, 2009; ICCT, 2011a). From a technology and design perspective, efficiency of ships can be improved through changes in engine and transmission technologies, auxiliary power systems, propellers, aerodynamics of the hull structure, electronically controlled engine systems to give fuel efficient speeds, and weight reduction (Notteboom and Vernimmen, 2009). These measures can increase the efficiency of new built vessels by 5-30%. Retrofit and maintenance measures can provide additional efficiency gains of around 4-20%, and combined technical and operational measures have been estimated to potentially reduce CO2 emissions by up to 43% per t-km between 2007 and 2020 and by up to 63% per t-km by 2050 (Crist, 2009). CO2 savings of 24% and 33% can be achieved by 2020 and 2030 respectively at a marginal cost below zero including fuel savings. Raising the marginal cost to USD 100 /tCO2 would increase the savings to 35% and 49% (Crist, 2009).

Operational changes to save fuel are possible for existing ships (WSC, 2011) including anti-fouling coatings to cut water resistance (Pianoforte, 2008) . Speed reduction by 10-20% ("slow-steaming") can directly cut CO2 emissions by 15--39% respectively (Corbett et al., 2009; Notteboom and

Vernimmen, 2009; ICCT, 2011a; Lindstad et al., 2011)(Corbett et al., 2009; Lindstad et al., 2011). As an example, total CO2 emissions from deep-sea container shipping were reduced by 11% between 2008 and 2010 (Pierre, 2011) and the resulting fuel savings more than compensated for the costs and emissions from running additional ships on some routes to maintain capacity (Meng and Wang, 2011).

Conversely, light-weighting of small or large ships, including hydrofoil ferries, can allow them to operate at higher speeds with little or no additional GHG emissions (Helms and Lambrecht, 2006). Wind propulsion systems (kites and parafoils) can provide lift and propulsion to reduce fuel consumption by up to 30%, though average savings may be much less (Kleiner, 2007).

8.3.2.6 Aviation

Substantial, on-going efficiency improvements in aircraft technology and design have been made over past decades (ITF, 2009). These typically offer a 20-30% reduction in energy intensity compared to the older models they will replace (IEA, 2009a). Further fuel efficiency gains of 40-50% in the 2030-2050 time frame (compared to 2005) could come from weight reduction, aerodynamic and engine performance improvements, and aircraft systems design (IEA, 2009a). However, the rate of introduction of major aircraft design concepts could be slow without significant new policy incentives or regulations at the regional or global level (Lee, 2010). The use of larger aircraft also has the potential to reduce CO_2 emissions significantly (Morell, 2009).

Due to long aircraft life and resulting slow turnover rates of aircraft fleets, operational measures and maintenance provide the best potential for short-term emission reductions (Peck Jr. et al., 1998; Lee, 2010) Retrofit opportunities, such as engine replacement and adding “winglets”, can also provide significant reductions (Marks, 2009; Gohardani et al., 2011).

Improving air traffic management also can reduce CO2 emissions through more direct routings and flying at optimum altitudes and speeds (Pyrialakou et al.) (Dell’Olmo and Lulli, 2003). Efficiency improvements of ground service equipment and electric auxiliary power units can provide some additional GHG reductions (Pyrialakou et al.).

8.3.3 Energy and carbon intensity reduction from new propulsion systems

At present, most vehicles and equipment across all transport modes are powered by ICEs, with gasoline and diesel the main fuels for LDVs; gasoline for 2- and 3-wheelers and small water craft; diesel for HDVs; diesel or heavy fuel oil for ships and trains (other than those using grid electricity); and kerosene for aircraft turbine engines. New propulsion systems include electric motors powered by batteries or fuel cells, turbines for rail and other ground vehicle applications, and various hybridized concepts.

8.3.3.1 Electric-drive road vehicles

Battery electric vehicles (BEVs) have attracted increasing attention in recent years as they emit no tailpipe emissions and very low fuel-production emissions when using low-carbon electricity (Kromer and Heywood, 2007). BEVs operate at a drive-train efficiency of around 80% compared with about 20-35% for conventional ICE LDVs, but at present, commercially available BEVs typically have a limited driving range of about 100-160km, long recharge times of 4 hours or more, and high battery costs leading to high vehicle retail prices (Greene and Plotkin, 2011).

Plug-in hybrid electric vehicles (PHEVs) with expanded battery storage and capable of grid recharging typically can operate on electricity alone for 20 to 50 km but emit CO_2 when their ICE is operating. Hydrogen FCVs generate electricity on board to power a motor, so need refuelling with hydrogen; however if combined with plug-in batteries, these would also be PHEVs and could also be recharged.

Gasoline or diesel fuel PHEVs do not have the range restrictions of BEVs, and thus could have lower public infrastructure requirements. The electric range of PHEVs is heavily dependent on the size of battery, design architectures, and control strategies for the operation of each mode (Plotkin et al., 2001). Since these systems allow a high share of driving on electricity for daily commuter driving patterns, they could provide a major shift to electricity with relatively small battery capacity compared to a dedicated BEV (Plotkin et al., 2001).

Future success and penetration of EVs will depend on improvements in battery technology (as reflected in battery cost reductions, reduced vehicle costs, improved performance, ease of recharging, extended life etc.) and the corresponding rollout of supporting recharging infrastructure. Lithium-ion batteries are currently dominant due to their high energy density and relatively long cycle life (Kromer and Heywood, 2007). The typical energy density of vehicle battery packs of 80-100 Wh/kg is targeted to reach 200-250 Wh/kg in 2020 (NEDO, 2010). Improving battery energy density and vehicle efficiency could reduce weight and extend driving range. The cycle life of a lithium-ion battery is about 1000 charges to below 80% depth of discharge, typically enough for 5~6 years of driving (NEDO, 2010). This lifespan is targeted to double by 2020. The present cost of full lithium-ion battery packs in early high-volume production is USD500-800 /kWh but is projected to drop below USD400 /kWh by 2015-2020 and below USD300 by 2030 (Element Energy, 2012; IEA, 2012d) . Cost per Wh capacity for PHEV battery packs under 30 km driving range are typically higher than for longer range EVs given the need for more power-oriented batteries, thereby offsetting some of the battery cost advantage of PHEVs (Element Energy, 2012).

In the road freight sector, the use of BEVs will likely be confined mainly to urban vehicles such as delivery vans whose drive cycles typically involve frequent stops and starts and a limited range (TIAX, 2009; AEA, 2011). Several studies have investigated the feasibility and cost-effectiveness of electrifying heavily-trafficked, inter-urban roads in northern Europe to permit direct transmission of electricity to ‘trolley trucks’ (Rach, 2010). This form of road freight electrification is likely to have limited and localised application over the next 10-20 years, partly because of its high capital cost. It has been estimated that electrifying German’s main autobahn network would cost EUR 15 billion (Wust, 2012). Sub-surface road wireless induction charging of stationary or moving vehicles is also under evaluation (Nathan, 2010; Covic and Boys, 2013).

Currently, about 1000 electric transit buses are operating in Chinese cities and being demonstrated elsewhere such as Adelaide where solar electricity is used for recharging (IEA, 2009). Electric two-wheelers are a mature technology with lower requirements for battery and motor capacities and widespread acceptance, especially in developing countries (Weinert *et al.,* 2008). There were over 120 million electric two-wheelers in China by the end of 2010 (Wu et al., 2011), implying an ownership of around one vehicle per ten people. The typical battery capacity for an electric two-wheeler is 576 Wh (20V-12Ah) which can support a range of about 60 km per-charge.

8.3.3.2 Fuel cell vehicles

Fuel cell vehicles (FCVs) can be configured with conventional, hybrid and plug-in hybrid drive-trains. Worldwide, there are estimated to be only a few hundred LDVs powered by fuel cells and a similar number of buses, all supported by around 250 hydrogen refuelling stations operating under demonstration programmes (Fuel Cells, 2011).

Since hydrogen can be produced by electrolysis using low carbon electricity sources, FCVs can reach very low fuel-cycle CO_2 emissions. However in the near to medium term, most FCVs will likely be powered by hydrogen reformed from natural gas methane since it is much cheaper and the well-to-tank efficiency is about 65-80% (IEA, 2012d). When using a fuel cell with efficiency of 54-61%, the full overall fuel-cycle efficiency of an FCV is about 35-49% (JHFC, 2011).

Over the past decade, the estimated large-volume production cost of proton exchange membrane (PEM) fuel cells deemed most suitable for LDVs has decreased from about USD275 /kW to under

USD100 /kW, with some estimates as low as USD50 /kW (DOE, 2011a). Higher estimates quote minimum fuel cell system material costs of USD150 /kW without assembly (Schoots et al., 2010). A typical 80 kW vehicle fuel cell system would therefore cost around USD 4 000 – 12,000 and in addition, a motor/controller system and hydrogen storage tanks costing around USD5 000 per vehicle based on existing technologies. Compressed hydrogen stored on-board the vehicle is commercially available and offers a driving range similar to today's gasoline/diesel LDVs but with a high cost increment. The estimated durability of a current fuel cell system is about 2500 hours (equivalent to around 125,000 km vehicle life assuming an average speed of 50 km/h), whereas a life span of 5000 hours is targeted (DOE, 2011a). Overall it could take another 5-10 years or longer for FCVs to achieve commercial readiness based on current oil and LDV purchase prices (IEA, 2012d).

8.3.3.3 Advanced propulsion technologies for rail, ships and aircraft

Rail systems tend to be very efficient, but improvements are possible. Diesel-hybrid locomotives have been demonstrated in the UK and advanced types of hybrid drive-trains under development in the US and Japan could save 10-20% of diesel plus around a 60% reduction of NO_x and particulate matter compared to conventional locomotives (JR East, 2011). An eventual shift to full electrification may enable many rail systems to reach very low CO_2 emissions where electricity generation has been deeply decarbonized. Fuel cell systems for rail may be attractive in areas lacking existing electricity infrastructure (IEA, 2012d).

For ships, full electrification is unlikely given the energy storage requirements for long-range operations, although on-board solar power generation systems could be used to provide auxiliary power and is already used for small craft. Solid-oxide fuel cell systems could be used, along with on-board reformers and liquid fuel storage (in the form of liquefied natural gas (LNG), alcohol or ammonia), though the cost of such systems remains relatively high as is nuclear power used in some navy vessels. Use of wind energy as a supplementary propulsion source is possible by using a hard sail rotor sail, or kite. However, it appears likely that most ocean-going ships will continue to use marine diesel engines for the foreseeable future, given their reliability and low cost (Crist, 2009).

For large commercial aircraft, no serious alternative to jet engines for propulsion has been identified, though fuel switching options are possible. For smaller/lighter aircraft, electric aircraft with advanced battery electric/motor systems could be deployed but would have limited range (Luongo et al., 2009).

8.3.4 Fuel carbon intensity reductions

In principle, low-carbon fuels from natural gas, electricity, hydrogen and biofuels (including biomethane) could all enable transport systems to be operated with low direct fuel-cycle CO_2-eq emissions, but this would depend heavily on their feedstocks and conversion processes (8.3.3.4).

8.3.4.1 Natural gas and LPG

Compressed natural gas (CNG, primarily methane) and liquefied petroleum gas (LPG, primarily propane and butane) commonly replace gasoline in Otto-cycle (spark ignition) vehicle engines after minor modifications to fuel and control systems, along with on-board compressed or liquefied storage of the fuel. These fuels can also be used in compression ignition engines but significant modifications are needed. Though the energy consumption of driving on CNG or LPG is typically similar to that for gasoline in similar vehicles, a reduction of up to 25% in tailpipe CO_2/km can be achieved because of differences in fuel carbon intensity. CNG systems also provide a bridge to lower carbon bio-methane systems from biogas (IEA, 2009).

Issues associated with use of CNG and LPG include the need for a gas distribution and refuelling infrastructure, vehicle conversion costs, possible loss of driving range and loss of on-board storage space (and payload on trucks) due to fuel storage tanks (IEA, 2010c).

Uptake of CNG vehicles has had considerable success in Pakistan (with the most NGVs operating in the world in 2010), India, Argentina, Brazil, and Italy, amongst others (IEA, 2010c). There are around 30 million CNG and LPG vehicles operating today, most being engine conversions since few original-equipment LDV models are available. Buses with CNG engines are more available and gained market share in many cities. For example, they now account for 20% of the US urban bus fleet (IEA, 2010c). LNG may have good application for HDVs and buses since it enables long-range travel between refuellings. Around 20,000 LNG buses are operating in China (Liu et al., 2012) and demonstration projects are underway elsewhere (Busworld, 2012).

8.3.4.2 Electricity

The GHG emissions intensity of power grids directly affects $CO_{2\text{-eq}}$ emissions from BEVs (and PHEV emissions when operating on electricity) (IEA, 2012d). The GHG intensity of a typical coal-based power plant is about 1000g CO_2-$_{\text{eq}}$/kWh at the outlet (Wang, 2012). For a BEV with efficiency of 200 Wh/km, this would emit about 200 g $CO_{2\text{-eq}}$/km which is higher than the 150 g $CO_{2\text{-eq}}$ /km typical for an efficient ICE or hybrid vehicle. When using electricity generated from nuclear or renewable energy, or from fossil fuels with CO_2 capture and storage, BEVs could achieve near-zero direct, well-to-wheel emissions.

The numbers of EVs in any country are unlikely to reach levels that significantly affect national electricity demand for at least one or two decades, during which time electricity grids could be at least partially decarbonized (IEA, 2012d). At least until a very large number of EVs are on the road, the use of off-peak (typically night-time) charging would enable existing power plant capacity to meet increased electricity demand (EUCAR/CONCAWE/JRC, 2008; Lemoine et al., 2008). EV users with home recharging facilities tend to use public recharging opportunities infrequently (Turrentine et al., 2011; Axsen and Kurani, 2012) but they do serve to reduce “range anxiety”.

zBEVs and PHEVs benefit from already well developed electricity systems, though upgrading the grid to include smart meters could help manage flexible charging schedules and added load from EVs (Sims et al., 2011). Public recharging locations would require significant infrastructure and related investments. New metering systems, time-of-day controlled charging, and vehicle-to-grid (V2G) storage continue to evolve. EV recharging from a grid could eventually yield the benefits of "peak shaving" (delaying charging from the grid during periods of high load) and "valley filling" (selling stored electricity back to the grid from vehicles at peak load times) (IEA, 2012d).

8.3.4.3 Hydrogen

Hydrogen used in FCVs or directly in modified ICEs can be produced using diverse resources, including reforming of coal, natural gas and biomass or via electrolysis using electricity from a range of sources. Steam methane reforming is well-established in commercial plants; electrolysis is commercial but relatively expensive; and biological processes are also possible. In selected locations, hydrogen available as a by-product from industrial processes could be used to fuel a number of FCVs if purification becomes cost efficient (Deng et al., 2010). Advanced, high-temperature and photo-electrochemical technologies are in early stages of R&D and could eventually become viable pathways (Arvizu and Balaya, 2011; IEA, 2012d).

Deployment of FCVs (8.3.2.2) needs to be accompanied by large, geographically focused investments into hydrogen distribution and vehicle refueling infrastructure, though the costs can be reduced by starting with specific locations (“lighthouse cities”)(Ogden and Lorraine, 2011) by and strategic placement of stations (Ogden and Nicholas, 2011). A high degree of coordination between fuel suppliers, vehicle manufacturers and policy makers is needed. Recent studies of hydrogen infrastructure build out in the United States suggest a capital investment of roughly $1400-2000 per vehicle would be needed (NRC, 2008; Ogden and Yang, 2009), roughly comparable to the cost of plug-in electric vehicle chargers on a dollar per car basis (NRC, 2008). Consistent with this, the cost of a fully developed hydrogen system, to support hundreds of millions of fuel cell vehicles around the world, is estimated to be in the order of USD 1-2 trillion, spent over several decades (IEA, 2012d). Though large, this would be less than 1% of projected total spending on transport (vehicles, fuels, infrastructure) over the same time frame (IEA, 2012d). The current cost of hydrogen production and delivery to vehicles is high compared with gasoline or diesel fuel, with steam reforming at point-of-use estimated to be about USD 1 per litre gasoline equivalent (lge), and electrolysis at point-of-use about USD1.50 /lge (IEA, 2012d). However, projected costs for high-volume, centralised hydrogen production via reforming coupled with low natural gas prices could see a drop to as low as USD0.50 /lge (DOE, 2011b). With distribution and refuelling costs added to the production cost in large central steam reformers, delivered hydrogen is estimated to be USD0.8-1.2 /lge, competitive with gasoline (Ogden and Lorraine, 2011). Decentralised hydrogen production may be the best choice for an initial market uptake period when vehicles are few and demand volumes are small, though building markets to the point where centralised production becomes viable appears an important objective (IEA, 2012d). In selected locations, hydrogen available as a by-product from industrial processes could be used to fuel a number of FCVs if hydrogen purification becomes cost efficient (Deng et al.,2010). Centrally produced hydrogen could initially be trucked to refuelling stations, and only when large regional markets are established would hydrogen pipelines be justified. The existence of natural gas pipelines may not help deliver hydrogen, given the specific requirements for transporting hydrogen in pipelines (IEA, 2012d).

8.3.4.4 Biofuels

A variety of liquid and gaseous fuels can be produced from biomass using a range of conversion pathways with different characteristics and costs. Biofuels met nearly 3% of world transport fuel consumption in 2011, a share that has risen fairly rapidly in recent years (IEA, 2012d).

In contrast to electricity and hydrogen, liquid biofuels are relatively energy-dense and are, at least in certain forms and blend quantities, compatible with all types of ICE vehicles, including cars, trucks, ships and aircraft. Most liquid biofuels can be blended at low levels with petroleum fuels for use in unmodified ICE vehicles, though ethanol generally requires some engine and fuel system modifications to go above 10% to 15% blends with gasoline, as does fatty-acid methyl ester (FAME) biodiesel to go above 10% to 20% blends with diesel fuel. Older vehicles may require lower blend limits. New ICE engines can be easily and cheaply modified during manufacture to accommodate much higher blends as exemplified by “flex-fuel” gasoline engines, where ethanol can reach 85% of the fuel blend (ANFAVEA, 2012) Like natural gas, bio-methane from suitably purified biogas or landfill gas and compressed, can also be used in today’s natural gas vehicles with only minor fuel system modifications (REN21, 2012). Creating an entire global fleet of vehicles capable of operating on high biofuel blends would take time given slow vehicle stock turnover rates, but would not be difficult to accomplish if the policies to do so were in place.

HDVs, ships and aircraft require energy dense fuels. Synthetic “drop-in” biofuels that are very similar to petroleum jet fuels are most suitable for aircraft (Caldecott and Tooze, 2009). They can be derived from a number of possible feedstocks and conversion processes, such as the hydro-treatment of vegetable oils or the Fischer-Tropsch conversion of biomass (Shah, 2013) but must adhere to very strict specifications. The ability to produce large volumes of biofuels cost-effectively and sustainably are the primary concerns for bio-jet fuels and similar for other biofuel applications (Sims et al., 2011).

Some biofuels have estimated fuel-cycle direct GHG emissions that are 30-90% lower than those for petroleum-based fuels, but when indirect emissions, including from land use change, are included they can be much higher (Wang et al., 2011). Including land-use change emissions can dramatically alter the comparison and determine whether or not a particular biofuel pathway provides net GHG reductions. Advanced biofuels produced from algae and ligno-cellulosic feedstocks such as grasses, short-rotation forests, and crop residues, offer potentially lower life-cycle emissions than grain or oil-seed based biofuels, and with better opportunities to avoid large direct and indirect land-use change impacts. Sugar cane ethanol is distinct since it is already commercial, widely produced (with Brazil the globally dominant but not the sole producer) and cost-competitive with gasoline in many contexts. The use of agricultural and forestry wastes and residues can avoid GHG emissions from land-use change and therefore result in very low net GHG emissions (Blottnitz and Curran, 2007). However, the alternative fate of wastes and residues must also be considered: net emissions may rise if waste diversion releases carbon that would otherwise be sequestered or utilized for other energy purposes (Blottnitz and Curran, 2007; Chester and Martin, 2009). The production of land-competitive biofuels can also have negative direct and indirect impacts on biodiversity, water and food availability (see Bioenergy Annex in Chapter 11).

The net effects of expanding biofuel production is a contentious topic, with little agreement at present on comparative methods (8.1.4) or quantitative results (Liska and Perrin, 2009; Delucchi, 2010; van der Voet et al., 2010; Delucchi, 2011; Malça and Freire, 2010; Wang et al., 2011; Johnson et al., 2011; McKone et al., 2011; Mullins et al., 2011; Taheripour et al., 2011; Cherubini and Strømman, 2011; Njakou Djomo and Ceulemans, 2012).

8.3.5 Comparative analysis

The vehicle and power-train technologies available for reducing fuel consumption and CO_2 emissions span a wide range and are not necessarily additive. When combined their overall potential should therefore be evaluated as an integrated fuel/vehicle system. To give valid conclusions regarding the optimal design of a transport system, further integration based on fuel characteristics, non-CO_2 emissions, passenger or freight occupancy factors, and indirect GHG emissions from vehicle manufacture and infrastructure are needed to gain a full comparison of the relative GHG emissions across modes (Hawkins et al., 2012; Borken-Kleefeld et al., 2013).

Taking LDVs as an example, simple assessments of future fuel consumption reduction potentials per kilometre out to 2030 for a range of LDV drive-trains and fuels have been compared with a 2005 baseline gasoline vehicle at about 8 lge /100km and 195 g/km CO_2 (Fig. 8.3.1). Using a range of incremental technologies, fuel economy can be improved by up to 50% (that is, energy consumption per km cut by half). Further improvements can be expected for hybrids, PHEVs, BEVs and FCVs, but several hurdles must be overcome to achieve wide market penetration (8.8). Any vehicle cost increases due to new technologies could affect potential market penetration, although they would be at least partly offset by fuel cost savings. However, such a comparison as this provides very limited information useful for policy-makers as it fails to include a number of key parameters including estimated life of vehicles, costs, manufacturing processes and materials, new infrastructure etc.

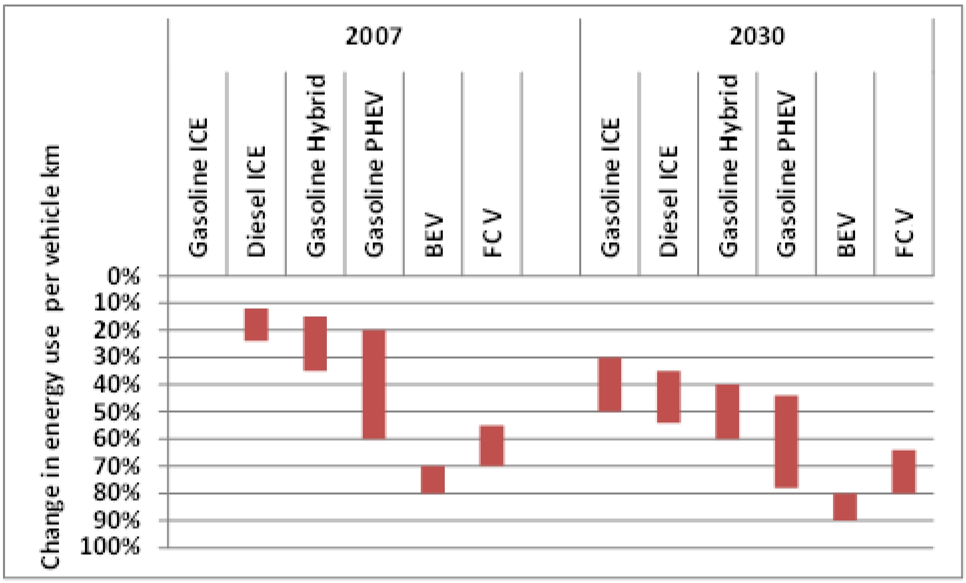
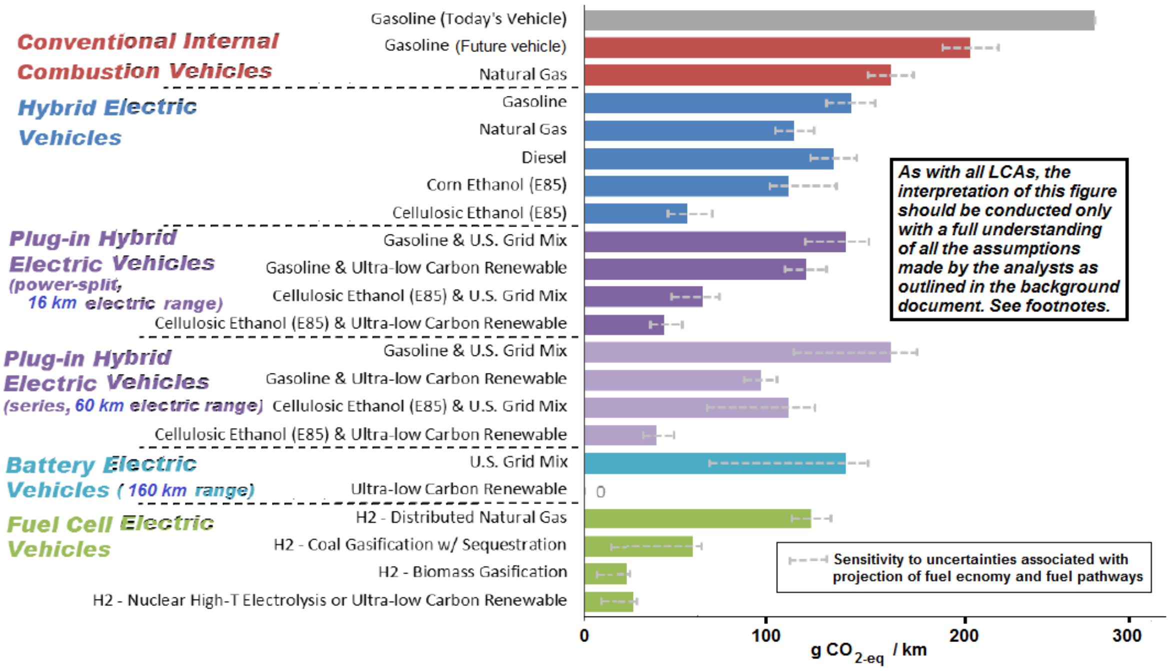


Figure 8.3.1. Indicative fuel consumption reduction potential ranges (% change in energy use per vehicle kilometre) for a number of LDV technology drive-train and fuel options in 2030, compared with a base gasoline ICE vehicle consuming 8 lge/100km in 2007 and other, then typical state-of-the-art, LDV drive-train and fuel technologies(Based on (IEA, 2009a; Kobayashi et al., 2009; Plotkin et al., 2009))

The present understanding of the climate effects of new vehicle and fuel systems is often based on life cycle assessment (LCA) (Annex II). It uses tools such as the Argonne National Laboratory's model GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) (Fig. 8.3.2). LCAs can be useful to compare the direct GHG emissions of alternative vehicles and fuels under a specific set of conditions, but have serious limitations that must be understood to properly interpret outputs (Tillman et al., 1994; Björklund, 2002; Fingerman et al., 2010; Hertel et al., 2010; McKone et al., 2011). The LCA example used here (Fig. 8.3.2) illustrates just one possible future scenario for the 2035-2045 timeframe. The outputs cannot be understood properly without a clear understanding of the details and assumptions made by the analysts. The notes below the figure address some of these, however the original document containing this figure (Nguyen and Ward, 2010) included seven pages of explanation, but some important assumptions and features still remained unclear, such as how the error bars were actually calculated.



As with all LCAs, the interpretation of this figure should be conducted only with a full understanding of all the assumptions made by the analysts as outlined in the background document. See footnotes.

Figure 8.3.2. Results of GREET model life-cycle analysis used to compare direct GHG emissions for light-duty vehicles in the United States, from a range of engine and fuel systems in the 2035-2045 time frame (Nguyen and Ward, 2010).

Notes:

- *"In a comparative study, the equivalence of the systems being compared shall be evaluated before interpreting the results. Consequently, the scope of the study shall be defined in such a way that the systems can be compared. Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision-rules on evaluating inputs, and outputs and impact assessment. Any differences between systems regarding these parameters shall be identified and reported"* (ISO, 2006).
- *LCA may account for some of the uncertainty associated with GHG emissions by varying time frames and key variables such as feedstocks for power generation and fuel production, but inevitably, important uncertainties will not be accounted for, such as the quantity of emissions outside system boundaries, which may be as high as 50%* (Lenzen, 2000; Arvesen et al., 2011).
- *LCA results are dependent on how the analysis is constructed, e.g. where system boundaries are drawn, how baseline fuels and vehicles are defined, etc.* (Farrell et al., 2006; Plevin, 2009; Huo et al., 2009; Luo et al., 2009; Hoefnagels et al., 2010; Malça and Freire, 2010; Wardenaar et al., 2012)*, yielding wide variations across studies in estimated GHG intensity ratings and even absolute preference order for vehicle technologies and fuels* (Farrell et al., 2006; van der Voet et al., 2010; Khatiwada et al., 2012).
- *Biomass-based fuels present special challenges because data on natural and agricultural systems are frequently poor and spatial and temporal variability is high* (Gibbons et al., 2006; Cherubini et al., 2009; Röös et al., 2010). *Accounting for indirect land use change (ILUC) requires examining overall system effects* (Searchinger et al., 2008; Melillo et al., 2009; Hertel et al., 2010)*) that are outside the boundaries of process-oriented LCAs. As a result, the estimated climate effects remain highly uncertain for many biofuels* (Delucchi, 2010; Hoefnagels et al., 2010; Malça and Freire, 2010; Plevin et al., 2010; Johnson et al., 2011; McKone et al., 2011).
- *The commonly-used LCA framework (attributional LCA, or ALCA) assumes that the GHG emissions scale linearly with quantity (i.e. the emissions estimated for a single liter of fuel can be scaled linearly to billions of litres of fuel)* (DeLuchi, 1993; Guinée et al., 2001; Ekvall et al., 2007)*, and that every liter of alternative fuel perfectly replaces an energy equivalent quantity of petroleum-based fuel, without affecting fuel markets* (DeLuchi, 1993; de Gorter, 2010; Arvesen et al., 2011). *Fuel switching and efficiency increases reduce global demand for petroleum-based fuels, resulting in lower prices and less GHG reduction than implied by engineering estimates* (Arvesen et al., 2011; Chen and Khanna, 2012; Rajagopal and Plevin, 2012; York, 2012).

- *A bar chart comparing ALCA results suggests that the difference in environmental effects between two products—such as a petroleum-based fuel and a biofuel—is simply the difference in the height of their respective bars. However, there is an important difference between interpreting the bar chart to mean, on the one hand, that "the ALCA rating of technology or fuel X is Z% lower than that of technology or fuel Y," and on the other, that "the technology or fuel X reduces emissions Z% compared to Y". The former correctly reflects the results of the analysis, regardless of its accuracy, while the latter treats the analysis as predictive, implying that (i) the heights of the bars reflects actual consequences, and (ii) product X perfectly substitutes for Y, without affecting its price or consumption (outside of this use) in any way. Neither of these implications can be deduced from an attributional LCA.*

8.3.6 Behavioural aspects

Behavioural change and its potential impacts on travel choices, modal mix, and uptake of new types of vehicles and fuels is complex. Some behavioural concepts are introduced here, mainly based on linkages to LDVs. Broader relationships between travel demand, modal choice, and their potential impacts on GHG emissions are covered in later sections.

There are a range of behavioural aspects related to the successful uptake of more efficient vehicles, new vehicle technologies and fuels; and the use of these vehicles in "real life" conditions.

- **Purchase behaviour:** It has been widely shown (Greene, 2010a) that consumers do not attempt to minimize the life-cycle costs of vehicle ownership. This characteristic leads to a considerable imbalance of individual costs and economy wide benefits. Individuals apply discount rates of 20% or more, which means that most car buyers do not account for fuel cost savings from better fuel economy beyond 2-3 years. Hence, only a fraction of the economy wide benefits (over the roughly 15 years potential lifetime of the vehicle) are taken into account when making a purchase decision (Kagawa et al., 2011). There is often a lack of interest in purchasing the more fuel efficient vehicles available on the market (Wozny and Allcott, 2010) due to credit constraints, imperfect information, information overload in decision making and consumer uncertainty about future fuel prices and the duration of their vehicle holdings (Anderson et al., 2011; Small, 2012). This suggests that in order to promote the most efficient vehicles, strong policies like fuel economy standards, sliding-scale vehicle tax systems or "feebate" systems (with tax variable based on fuel economy or CO2 emissions) may be needed (8.10) (Gallagher and Muehlegger, 2011).

- **New technologies/fuels:** Lack of willingness to purchase new types of vehicles with significantly different attributes (such as smaller size, shorter range, longer refuelling or recharging time, higher cost) is a potential barrier to introducing new propulsion systems and fuels (Brozović and Ando, 2009). This may relate simply to the perceived quality of various attributes or to risk aversion and uncertainty (such as range anxiety for BEVs) (Wenzel and Ross, 2005). The extent to which policies must compensate by providing incentives varies but may be substantial. The recent slow market introduction of BEVs even in countries with generous incentives suggests this is the case (Gallagher and Muehlegger, 2011).

- **On-road fuel economy:** The tested fuel economy of a new vehicle can be up to 30% better than that actually achieved by an average driver on the road (IEA, 2009). This gap may be increasing in recent years and with some new vehicle models (TMO, 2010; ICCT, 2012). This gap reflects a combination of factors including inadequacies in the test procedure, real-world driving conditions (e.g. traffic, road surface, weather conditions), driver behaviour, and vehicle age and maintenance. Some countries attempt to adjust for these differences in their vehicle fuel economy information. The gap between 5-10% improvement in on-road fuel economy can be achieved through efforts to promote "eco-driving" (IEA, 2012d). Another 5-10% may be achievable by an "integrated approach" including better traffic management, intelligent transport systems and better vehicle and road maintenance.

- **Driving behaviour with new types of vehicles:** Taking EVs as an example, the frequency of use of public recharging systems, day/night recharging patterns, etc. could affect how much these vehicles are driven, when and where they are driven, and potentially their GHG emissions impacts (e.g. based on time-of-day charging) (Axsen and Kurani, 2012). Research in this area is still immature.
- **Driving rebound effects:** Changes in reaction to lowering the cost of travel (through fuel economy measures or using budget airline operators) is commonly called the (direct) "rebound effect" (Greene et al., 1999). In North America this has been found to be in the range of a -0.05 to -0.30 fuel cost elasticity (e.g. a 50% cut in the fuel cost of driving results in a 2.5% to 15% increase in driving) with some studies finding it is declining and may be at the low end of this range (Hughes et al., 2006; Small and van Dender, 2007; EPA, 2012). The rebound effect may be higher in countries with more modal choice options or where price sensitivity is higher, but research is poor for most countries and regions outside the OECD. The rebound can be addressed by fuel taxes or road pricing that offset the lower travel cost created by efficiency improvements or reduced oil prices, which may be the result of reduced demand from increased efficiency or fuel switch (8.10) (Hochman et al., 2010; Rajagopal et al., 2011; Chen and Khanna, 2012).
- **Vehicle choice-related rebounds:** Other types of rebound effect are apparent, such as purchase shifts to larger cars concurrent with shifts from gasoline to diesel vehicles in Europe, perhaps linked to the lower driving costs of diesels (Schipper and Fulton, 2012). For freight, shifts to larger HDVs and otherwise less expensive systems can divert freight from lower carbon modes, mainly rail, and induce some additional freight movement (Umweltbundesamt, 2007). These rebound effects have been estimated to be modest so do not negate load consolidation benefits on the road network (TML, 2008; Leduc, 2009).

8.4 Infrastructure and systemic perspectives

Transport modes and their infrastructures form a system that has evolved technologically into the current stage of maturity. For example, auto-mobility can be understood culturally as a self-reproducing system composed of manufactured cars, related consumption and status; inter-linkages to other industries, urban and land-use planning; the quasi-private nature of the automobile framing life-style and putting constraints on leisure, family and work life; and a culture sustaining good quality of life with respect to mobility (Urry, 2007).

8.4.1 Path dependencies

Systemic change tends to be slow and needs to address path dependencies embedded in sunk costs, high investment levels and cultural patterns. Technological change in vehicles, infrastructure and fuels, changes in spatial settlement patterns, and behavioural change in the systemic use of infrastructures, will need to either adapt to the existing system or seek to create and sustain lower GHG-emissions alternatives. Future developments to improve infrastructure in developing countries will decisively determine the energy intensity of transport and concomitant emissions in these countries (Lefèvre, 2009), requiring urgent policies and actions.

8.4.1.1 GHG emissions impacts from infrastructure

The construction, operation, maintenance and eventual disposal of transport infrastructure (such as rail tracks, highways, ports and airports), all result in GHG emissions. Full accounting of life-cycle analysis (LCA) emissions requires these infrastructure-related emissions to be included along with those from vehicles and fuels (8.3.5). GHG emissions per passenger-kilometre (p-km) or per tonne-kilometre (t-km) depend, *inter alia*, on the intensity of use of the infrastructure and the share of tunnels, bridges, runways etc. (Åkerman, 2011b; Chang and Kendall, 2011; UIC, 2012). In the USA, GHG emissions from infrastructure for LDVs, buses and air transport amount to 17-45 g/p-km, 3-17 g/p-km and 5-9 g/p-km respectively (Chester and Horvath, 2009) with rail between 3-11 g/p-km (Table 8.4.1). Opportunities exist to substantially reduce infrastructure related emissions, for instance by up to 40% in rail (Milford and Allwood, 2009), by the increased deployment of low-carbon materials and recycling of rail track materials at their end-of-life (Network Rail, 2009; Du and Karoumi, 2012). If rail systems achieve modal shift from road vehicles, emissions from the rail infrastructure may be partially offset by reduced emissions from road infrastructures (Åkerman, 2011b). To be policy-relevant, LCA calculations that include infrastructure need to be contextualized with systemic effects such as modal shifts (8.4.2.3 and 8.4.2.4).

Table 8.4.1. Rail transport infrastructure GHG emissions based on LCA data.

Mode/component	**Emissions** (g $CO_{2\text{-eq}}$/p-km)	**Reference**	**Comment**
Swedish high-speed rail plans	5.1	(Amos et al., 2010; Åkerman, 2011b)	At 25 million passengers per year, double track (double capacity) would halve infrastructure emissions
Vehicle emissions; Swedish high speed rail plan	1.0	(Åkerman, 2011b)	
ICE system study	9.7	(Von Rozycki et al., 2003)	About half emissions from infrastructure including non-high speed stretches.
High-speed rail infrastructure	3.1-10.9	(Tuchschmid, 2009)	Low emission value for 90 trains per day, high emission value for 25. Current EU network is at 6.3 g/p-km
USA high-speed rail plans	3.2 g/pkm	(Chang and Kendall, 2011)	This 725 km line will emit 2.4 million t $CO_{2\text{-eq}}$ per year

Existing vehicle stock and infrastructure prescribe future use and can lock-in emission paths for decades while inducing similar investment because of economies of scale (Shalizi and Lecocq, 2009). Infrastructure economic life-cycles range from 50 to more than 100 years. This makes the current development of infrastructure critical to the mode shift opportunities of the future. For example, the US interstate highway system and lack of an extensive passenger rail system determines a demand-side lock-in produced by the complementarity between infrastructure and vehicle stock. The construction of the highway system induced an acceleration in growth of vehicle miles travelled (VMT) around 1970, and ex-urban development away from city centres created a second peak in transport infrastructure investment post 1990 (Shalizi and Lecocq, 2009). Conversely the current high level of high speed rail infrastructure in China (Amos et al., 2010) may provide low emission alternatives. Accounting for substantial new traffic generated by new rail lines, a net reduction of emissions will occur at a minimum of between 10 and 22 million passengers annually (Westin and Kågeson, 2012).

Aviation and shipping require point infrastructures (ports) but no line infrastructures (with the exception of channels and navigable rivers and lakes for inland shipping), so tend to have a relative low infrastructure share of total life-cycle emissions. Rising income and partially declining airfares have led to increased air travel (Schäfer, 2009), correlating with new construction and expansion of airports. Taxing fuels, tickets or emissions may reduce air transport volume with elasticities varying between -0.3 to -1.1 at national and international level (InterVISTAS Consulting Inc., 2007), but with strong regional differences (Europe has 40% stronger elasticities as most other world regions). Though airport congestion may add to emissions (Simaiakis and Balakrishnan, 2010), it also tends to moderate air transport demand growth to give a net reduction of emissions at network level (Evans and Schäfer, 2011).

8.4.2 Path dependencies of urban form and mobility

Transport demand and land use are closely inter-linked. In low-density developments with extensive road infrastructure, LDVs will likely dominate mode choice for most types of trips. Walking and cycling can be made easier and safer, where high accessibility to a variety of activities are located within relative short distances (Ewing and Cervero, 2010). Conversely the stress and physical efforts of cycling and walking can be greater in cities that consistently prioritize suburban housing developments leading to distances that accommodate the high-speed movement and volume of cars (Naess, 2006). The choice to use an LDV can lead to CO_2 emissions, congestion, air pollution and noise (so can be termed non-cooperative behaviour), whereas the choice of public transport or non-motorized transport (co-operative behaviour) is socially advantageous by comparison (8.7) (Camagni et al., 2002a); (Creutzig and He, 2009)). Sustainable urban planning offers tremendous opportunities. An additional 1.1 billion people will live in Asian cities in the next 20 years (ADB, 2012a), yet relatively few have plans to promote smart growth, urban form and infrastructure to avoid future transport congestion or shift future motorized travel to more sustainable modes.

Urban population density correlates with GHG emissions from land transport (Newman and Kenworthy, 1996; Kennedy et al., 2011; Rickwood et al., 2011) and enables non-motorised modes to be more viable (Newman and Kenworthy, 2006). Both aggregated and disaggregated studies that analyse individual transport use confirm the relationship between land-use and travel (Weisz and Steinberger, 2010; Kahn Ribeiro et al., 2012). Land use, employment density, street design and connectivity, and high transit accessibility also contribute to reducing car dependence and use (Handy et al., 2002; Ewing, 2008; Cervero and Murakami, 2009; Olaru et al., 2011). The built environment impacts travel behaviour and residential choice (Naess, 2006; Ewing and Cervero, 2010), but self-selection (residential choice) plays a substantial role that is not easy to quantify (Cao et al., 2009)(Ewing and Cervero, 2010). In the US population density and job density had surprisingly little effect on journey distance once controlled for accessibility of destinations and street network design (Ewing and Cervero, 2010).

There exists a non-linear relationship between urban density and modal choice. Suburban residents drive more and walk less than residents living in inner city neighbourhoods (Cao et al., 2009) and public transit is more difficult to deploy successfully in suburbs with low densities (Frank and Pivo, 1994). In low density areas, para-transit[3] options can complement individualized motorized transport more efficiently and with greater customer satisfaction than public transport (Baumgartner and Schofer, 2011). Demand-responsive, flexible transit services can have lower GHG emissions per passenger kilometre with higher quality service than regional public transport (Diana et al., 2007; Mulley and Nelson, 2009; Velaga et al., 2012). In Switzerland, for example, a car-sharing service with nearly 100,000 patrons serves low-density areas and reduces annual CO_2 emissions by 290 kg per participant (Loose, 2010).

Land use diversity, intersection density, and the number of destinations within walking distance are identified variables for walking modal choice. In the US, public transport use is equally related to proximity to transit and street network design variables, with land use diversity a secondary factor (Ewing and Cervero, 2010) but these results cannot be directly applied to all demographic groups (Figueroa, Sick, et al., 2013) or translated to other world regions.

8.4.2.1 *Modal shift opportunities for passengers*

Small but significant modal shifts from LDVs to bus rapid transit (BRT) have been observed as they can offer similar benefits as metro systems at much lower costs (Deng and Nelson, 2011). Approximately 147 cities have implemented BRT systems, serving nearly 25 million passengers daily

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[3] Para-transit, also called community-transit, is where flexible passenger transport minibuses (matatus, marshrutka), shared taxis and jitneys usually operate in areas with low population density without following fixed routes or schedules.

(Deng and Nelson, 2011; BRT, 2012). Capital costs are lower than light rail and metro systems, though these can have lower CO_2 emissions and metro can reach higher capacities (Table 8.4.2).

Table 8.4.2. Comparison of capital costs, direct CO_2 emissions and capacities for BRT, light rail and metro urban mass transit options (IEA, 2012d).

	Bus rapid transit	**Light rail**	**Metro**
Capital cost (USD millions/km)	5 to 27	13 to 40	27 to 330
Network length that can be built for USD 1 billion (km)	37 to 200	25 to 77	3 to 37
World network length in 2011 (km)	2139	15,000	10,000
Direct CO_2 intensity (gCO_2/pkm)	14 to 22	4 to 22	3 to 21
Capacity (thousand passengers per hour per direction)	10 to 35	2 to 12	12 to 45

A shift from NMT to LDV transport occurred during the last century, initially in OECD countries and then globally. However, Increases in cycling and walking now appear to be happening in many cities though accurate data is scarce (Bassett et al., 2008b; Pucher et al., 2011). In Germany, Netherlands, Denmark and elsewhere, cycling modal shares have increased since the 1970s and are now between 10-25% (Pucher and Buehler, 2008). Some carbon emission reduction has resulted from cycle infrastructure deployment in Barcelona, Copenhagen, Freiburg, and Malmö (COP, 2010; Rojas-Rueda et al., 2011; Creutzig et al., 2012a) and in some cities in South and North America (USCMAQ, 2008; Schipper et al., 2009; Massink et al., 2011; USFHA, 2012). Walking and cycling trips vary substantially between countries, accounting for over 50% of daily trips in the Netherlands and in many Asian and African cities (mostly walking); 25%-35% in most European countries; and approximately 10% in the US and Australia (Pucher and Buehler, 2010; Leather et al., 2011; Pendakur, 2011). Land use and transport policies considerably influence bicycle modal share (Pucher and Buehler, 2006), notably, provision of separate cycling facilities along heavily traveled roads and at intersections and traffic calming of residential neighbourhoods (NRC, 2011b; Andrade et al., 2011). Many Indian and Chinese cities with traditionally high levels of walking are now reporting dramatic decreases (Leather et al., 2011). Deliberate policies based around design principles have increased modal share of walking and cycling in Copenhagen, Melbourne and Bogota (Gehl, 2011). Public bicycle share systems have created a new mode for cities (Shaheen et al., 2010), with many cities now implementing extensive public cycling infrastructure resulting in increased bicycle modal share (DeMaio, 2009).

Public transport, walking and cycling are closely related. Around 90% of all public transport trips are connected with a walk trip in the US and 70% in Germany (Pucher and Buehler, 2010). With rising income and urbanization, there will likely be a strong pull toward increasing car ownership and use in many countries. However, public transit mode shares have been preserved at fairly high levels in cities that have achieved high population densities and that have invested heavily in high quality transit systems (Cervero, 2004). Investments in mass rapid transit timed with income increases and population size/density increases have been successful in some Asian megacities (Acharya and Morichi, 2007). As traffic congestion grows and freeway infrastructure reaches physical, political and economic limits, the modal share of public transit has increased in some OECD countries (Newman and Kenworthy, 2011a).

High-speed rail can substitute for short-distance (up to around 800km) passenger air travel and most road travel and hence mitigate GHG emissions (McCollum et al., 2010) IEA, 2008). With optimized operating speeds and distances between stops, and high passenger load factors, energy use per passenger-km could be as much as 65 to 80% less than air travel (IEA, 2008). Notably, China shows a fast development of its high-speed rail system (8.3.1.4) which, when combined with strong land-use and urban planning, has the potential to restructure urban development patterns, and may help to alleviate local air pollution, noise, road and air congestion (McCollum et al., 2010).

8.4.2.2 Modal shift opportunities for freight

Over the past few decades, air and road freight have increased their share of the market at the expense of rail and waterborne transport (European Environment Agency, 2011; Eom et al., 2012). This is due to economic development and the related change in the industry and commodity mix, often reinforced by differential rates of infrastructure improvement and the deregulation of the freight sectors, which typically favours road transport. Inducing a substantial reversal of recent freight modal split trends will be difficult, *inter alia* because of 'structural inelasticity' which confines shorter distance freight movements to the road network because of its much higher network density (Rich et al., 2011). If growth in global truck travel between 2010 and 2050 could be cut by half from the projected 70% and shifted to expanded rail systems, about a 20% reduction in fuel demand and CO_2 could be achieved, with only about a fifth of this savings being offset by increased rail energy use (IEA, 2009). The European Commission set an ambitious target of having all freight movements over distances greater than 300km to use rail or waterborne modes by 2030 leading to major changes in modal shares (Fig. 8.4.1) (Tavasszy and Meijeren, 2011).

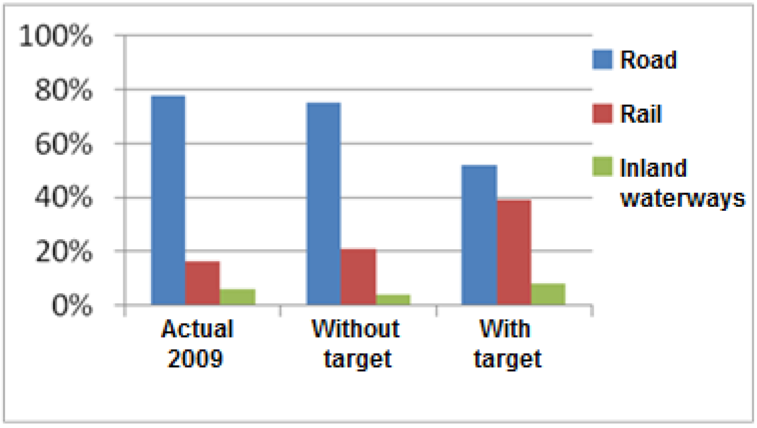

Figure 8.4.1. Projected freight modal split in the EU 25 in 2030 comparing 2009 shares with business-as-usual without target and with EU White Paper modal split target **(Tavasszy and Meijeren, 2011)**.

The capacity of the European rail network would have to at least double to handle this increase in freight traffic and the forecast growth in rail passenger volumes, even if trains get longer and run empty less often (CE Delft, 2011). Longer-term transformations need to take account of the differential rates at which low-carbon technologies could impact on the future carbon intensity of freight modes. Applying current average intensity values (8.3.3) may result in over-estimates of the potential carbon benefits of the modal shift option. The rate of carbon-related technical innovation, including energy efficiency improvements, has been faster in HDV than rail freight and the vehicle replacement rate is typically much shorter ensuring a more rapid uptake of new technology uptake.

The potential for shifting freight to greener modes is difficult in urban areas. Intra-urban rail freight movements are possible (Maes and Vanelslander, 2011) but city logistical systems are almost totally reliant on road vehicles and likely to remain so. The greater the distance of land haul for freight, the more competitive the lower carbon modes become. Within cities, the concept of modal split needs to be redefined and related to the interaction between personal and freight movement. Currently large amounts of freight on the so-called 'last mile' to a home or business are carried in LDVs and public transport vehicles. With the rapid growth of on-line retailing, much of this private car-borne freight, which seldom appears in freight transport statistics, will be transferred to commercial delivery vans. Comparative analyses of conventional and on-line retailing suggest that substituting a van delivery for a personal shopping trip by private car can yield a significant carbon saving (Edwards et al., 2010).

At the international level, opportunities for switching freight from air to shipping services are limited. The two markets are relatively discrete and the products they handle have widely differing monetary values and time-sensitivity. The deceleration of deep-sea container vessels in recent years in accordance with the ‘slow steaming’ policies of the shipping lines has further widened the transit time gap between sea and air services. Future increases in the cost of fuel may, however, encourage businesses to economize on their use of air-freight, possibly switching to sea-air services in which products are air-freighted for only part of the way. This merger of sea and air transport offers substantial cost and CO_2 savings for companies whose global supply chains are less time-critical (Conway, 2007; Terry, 2007).

8.5 Climate change feedback and interaction with adaptation

Transport is impacted by climate change both positively and negatively. Data and literature on the inter-relationship between mitigation and adaptation in the transport sector are still relatively limited. This inter-relationship depends on regional variations in climate change and the nature of local transport infrastructure and systems.

8.5.1 Accessibility and feasibility of waterborne transport routes

Decreases in the spatial and temporal extent of ice cover in the Arctic and the Great Lakes region of North America have opened the potential for new and shorter shipping routes and may allow these to remain open for longer periods (Prowse and Brown, 2010) (Drobot et al., 2009; Stephenson et al., 2011). These routes could save fuel and decrease emissions compared to some current routes. For example, the Northern Sea Route (NSR) between Shanghai and Rotterdam is about 40% shorter than the route via the Suez canal and takes approximately ten days less to complete (Verny and Grigentin, 2009; McKinnon and Kreie, 2010). The transport of oil and gas through the NSR could increase from 5.5 Mt in 2010 to 12.8 Mt by 2020 (Ho, 2010). Though there are few estimates of likely demand, this passage may also become a viable option for other bulk carriers and container shipping in the near future (Verny & Grigentin, 2009; Schøyen & Bråthen, 2011). However, the economic viability of the NSR is still uncertain (Liu and Kronbak, 2010). (Xu et al., 2012) estimated that the annual fuel cost of a container fleet using the seasonal NSR alternative can be saved 3–5%, but there will be several limitations such as poor port infrastructure and ice-free conditions may not necessarily mean optimal navigation conditions. Opening previously frozen waterways could increase shipping through sensitive ecosystems that could lead to an increase in local environmental impacts unless additional emissions controls are implemented (Wassmann, 2011). For example, emissions of black carbon and the precursors of photochemical smog in the Arctic could lead to additional local positive regional climate forcing (Corbett et al., 2010).

Changes in climate are also likely to affect inland waterways due to lower water levels in summer (Jonkeren et al., 2007; Millerd, 2011)(Jonkeren et al., 2007). In winter, however, in high latitudes lower incidence of freezing events is likely to increase the use of inland waterways. Both effects are likely to affect modal choice for freight transport positively and negatively (Jonkeren et al., 2011), the net effect remaining uncertain.

8.5.2 Relocation of production, international trade and global supply chains

Climate change is likely to alter the zoning of agricultural production. A number of scenarios indicate changing patterns of crop yields are likely to be pronounced in Africa and parts of Asia (Nielsen and Vigh, 2012; Teixeira et al., 2012). This could result in the reconfiguring of agri-food supply chains (Tirado et al., 2010). The net effect on routing and the total amount of freight movement is uncertain (Vermeulen et al., 2012). The geography of present biofuel production and distribution could also be influenced by climate change (De Lucena et al., 2009).

Globally interconnected supply chains and logistics are particularly vulnerable to the integration of geographically dispersed networks of production and the sourcing of goods on a just-in-time basis (Henstra et al., 2007; Love et al., 2010). Extreme weather events are one of many risk factors to which supply chains are exposed, but, as illustrated by 2011 flooding in Thailand and the 2012 superstorm "Sandy" in North Eastern US and airport closures, they can cause extensive logistical disruption. International initiatives have been launched to reduce the exposure of supply chains to risk and improve their resilience (World Economic Forum, 2012). Some risk-mitigation measures, such as returning to more localised sourcing and relaxing just-in-time pressures, are likely to reduce GHG emissions whereas others, such as increasing the availability capacity to deal with weather extremes, may carry a carbon penalty.

8.5.3 Urban form and infrastructure

Increasing population density in urban areas can enhance transport efficiency (8.4) and foster mitigation efforts in other energy end-use sectors such as buildings (9.3). However, higher density may also increase the exposure of a larger number of people to extreme weather events (IPCC, 2012). Hence, the integration of mitigation and adaptation objectives in urban planning is vital to manage GHG emissions in cities without increasing vulnerability (Romero-Lankao and Dodman, 2011).

Climate proofing and adaptation will require substantial infrastructure investments (see IPCC AR5,WG II, Chapter 15), which may generate additional freight transport if implemented outside of the normal infrastructure maintenance and upgrade cycle. Climate proofing of transport infrastructure can take many forms (Eichhorst, 2009; ADB, 2011a; Highways Agency, 2011) including varying freight-transport intensity. Resurfacing a road with more durable materials to withstand greater temperature extremes may require no additional freight movement, whereas re-routing a road or rail link or installing flood protection may potentially generate additional logistic demand, which has yet to be quantified.

Adaptation efforts are likely to increase transport infrastructure costs (Hamin & Gurran, 2009)~~,~~ and influence the selection of projects for investment. In addition to inflating maintenance costs (Jollands et al., 2007; Larsen et al., 2008), climate proofing would divert resources that could otherwise be invested in extending networks and expanding capacity. This is likely to affect all transport modes to varying degrees. If, for example, it were to constrain the development of a rail network more than road infrastructure, it might inhibit a modal shift to less carbon-intensive rail services.

The future choice of freight and passenger traffic between modes may also become more sensitive to their relative sensitivity to extreme weather events (Koetse and Rietveld, 2009; Taylor and Philp, 2010). The exposure of modes to climate risks include aviation (Eurocontrol, 2008), shipping (Becker et al., 2012) and land transport (Hunt and Watkiss, 2011). Little attempt has been made to conduct a comparative analysis of their climate risk profiles, to assess the effects on the modal choice behaviour of individual travellers and businesses, or to take account of regional differences in the relative vulnerability of different transport modes to climate change (Koetse and Rietveld, 2009).

8.5.4 Fuel combustion and technologies

Increased ambient temperatures and humidity levels are likely to affect nitrogen oxide, carbon monoxide, methane and black carbon (particulate) emissions from ICEs using a range of fuels including biofuels and heavy fuel oils (STUMP et al., 1989; Rakopoulos, 1991; Cooper and Ekstrom, 2005; Motallebi et al., 2008) Lin and Jeng, 1996; McCormick et al., 1997; Pidolal. 2012) Higher temperatures also lead to higher evaporative emissions of volatile organic compound emissions (VOCs) (Roustan et al., 2011) and could lead to higher ozone levels (Bell et al., 2007). The overall effects are uncertain and could be positive or negative depending on regional conditions (Ramanathan & Carmichael, 2008).

As global average temperatures increase, the demand for on-board cooling in both private vehicles and public buses and trains is likely to increase. The heating of vehicles could also grow as the frequency and severity of cold spells increase. Both reduce average vehicle fuel efficiencies. In a passenger LDV, air-conditioning can increase fuel consumption by around 3-5% (Farrington and Rugh, 2000; IEA, 2009a). Increased heating or cooling of entire bus and train stations may also affect energy consumption of public transport (Koetse and Rietveld, 2009).

Extremes in temperature (both high and low) negatively impact on the driving range of electric vehicles due to greater use of on-board heating and air conditioning, and so will require more frequent recharging. Energy consumption and emissions will also increase in temperature-controlled supply chains for food and other products subject to decomposing (James and James, 2010).

8.6 Costs and potentials

The potential for reducing GHG emissions in the transport sector, as well as the associated costs, will vary widely across countries and regions, as will the appropriate policies and measures that can accomplish such reductions (8.10) (Kahn Ribeiro S, et al., 2007; Li, 2011). Mitigation costs and potentials are a function of the stringency of climate goals and their respective GHG concentration stabilization levels (Fischedick et al., 2011; Rogelj et al., 2012). This section is organized around the decomposition into activity, structure, energy intensity and fuel carbon intensity (Fig. 8.1.2).

8.6.1 Activity demand reduction

Climate change constitutes only a relatively minor part of negative transport externalities (8.7, 8.8) (Calthrop and Proost, 1998; Delucchi and McCubbin, 2011; Friedrich and Quinet, 2011; (Proost, 2011). Most negative transport externalities, such as congestion and local air pollution, occur in cities, particularly those dominated by LDVs (Maibach et al., 2007; Button, 2010). Reducing motorized transport in general, and car usage in cities in particular, can be a reasonable goal but the cost-benefit evaluation depends on many local factors, including population density, modal share, urban form and local climate (Proost, 2011).

Depending on the specific city, a reduction in urban transport activity could range between 0-30% (TFL, 2007; Eliasson, 2008; Creutzig and He, 2009). Cost-benefit evaluations of congestion charges, a policy used in some cities, have demonstrated negative costs (i.e. benefits) are possible from activity reduction (TFL, 2007; Eliasson, 2008). Taking quantifiable externalities into account, a case study of Beijing suggests that about a 30% over-provision of car transport exists there (Creutzig and He, 2009). Optimising the congestion level at 2005 levels would have corresponded to a reduction of emissions of 8 Mt CO_2 /yr. Such an activity reduction produces social benefits from saved time and improved public health. Costs relate only to the measure of activity reduction such as implementing a congestion charge, which can still be substantial (Prud’homme and Bocarejo, 2005)Prud’homme and Bocarejo, 2005)

. An alternative to road pricing, but complementary, could be to provide more street space for pedestrians, cyclists and public transit (Gehl, 2011).

Significant potential exists for mitigation by urban planning to include policies that target density, destinations, accessibility, distance to transit, diversity, mixed use, design-quality, and demand management – the “6 Ds” (Ewing and Cervero, 2010). This potential could be exploited in cities and metropolitan areas that have followed low-density and car-oriented patterns of urban development. Estimates for the US suggest that densifying urban development over about half a century could reduce annual CO_2 emissions from vehicle fuels by 9–16% (Ewing, 2007). By densifying automobile-dependent suburbs, driving could be reduced by 20-40% compared to baseline development (Ewing, 2007). Cities with rapid population growth offer notably higher potential for mitigation by urban planning than other cities (Creutzig et al., 2012a). Reducing urban sprawl and densifying US cities could reduce emissions by at least 10 $GtCO_2$ during the period 2005-2054 (Marshall, 2011). Polycentric city policies have been suggested by the World Bank as the foundation for a cost-effective response to climate change (Ostrom, 2009) And many Indian and Chinese cities are now pursuing such policies following the successful Singapore model (Jenks et al., 2008; Newman and Matan, 2013a). LDV use in Australian cities could be reduced by 50% if polycentric city policies were to be implemented, as urban density has an exponential link, not linear, with car use (Newman et al., 2009). The most cost-effective option is to maintain high density in cities that are not (yet) car-dependent (ADB, 2012a; Bongardt et al., 2013).

For freight, the amount of movement (t-km) differs from the level of freight traffic (vehicle–km). Given the close correlation between movement and GDP at the national level (Kamakaté and Schipper, 2009a; Eom et al., 2012) and strong globalisation pressures, it would be difficult to restrain the underlying growth in freight without inhibiting the process of economic development (Harris et al., 2011). However, it could be achieved by returning to more localised sourcing, manufacture and storage of products, thereby shortening supply chains, or by the routing of freight more efficiently across these supply chains. The channelling of freight traffic through a smaller number of major logistical hubs (Sheffi, 2012) could make routing more circuitous, hence further inflating the total t-km. At the local level, greater deployment of computerised vehicle routing systems could partly offset this trend.

8.6.2 Structure and modal shift

Globally, a 25% reduction in passenger travel by 2050 (relative to baseline growth) would lead to an estimated 20% reduction in energy demand and related CO_2 emissions, half of this from modal shifts to rail, bus, and non-motorised travel, and half eliminated through better urban planning and telematics substitution (IEA, 2009; (Cuenot et al., 2012). A combination of technology measures, public transport and NMT supply measures, pricing instruments, and land-instruments might bring about a 60% reduction in CO_2 emissions in some European cities by 2040 (Creutzig et al., 2012a).

The costs associated with such modal shifts include the change in capital cost of providing the infrastructure and vehicles to accommodate the changes and the operating/maintenance/energy costs of providing the alternative transport service translating into marginal costs to travellers and infrastructure costs to taxpayers

Infrastructure costs can be high (as for high-speed rail systems) or low (as for reassigning road lanes to cyclists or inter-urban bus transport) (Sælensminde, 2004) (Wang, 2011); (Gotschi, 2011) but the net cost/benefit depends on many factors. Redevelopment of an Australian suburb around walking and mass transit reduced GHG emissions compared with developing a car dependent suburb (Trubka et al., 2010a). Cost savings for each new transit-oriented household were USD 85,000 for non-transport infrastructure savings; USD 250,000 over 50 years for public and private transport savings; USD 2 900 social cost for GHG emissions assuming USD 25/$tCO_{2\text{-eq}}$ (or USD 24,990 at USD 215/$tCO_{2\text{-eq}}$; USD 4 230 for health savings from reduced obesity; and USD 34,450 from increased productivity due to increased walking.

Given the huge differences in transit times and freight rates, the air and sea freight markets are essentially discrete and offer little opportunity for mode switching, though more companies could be encouraged to use combined sea-air services which are much less carbon-intensive than pure air cargo services. Relaxation of just-in-time (JIT) sourcing would make it easier for slower, less carbon intensive modes to increase their share of the freight market, though the wider effects of JIT on GHG emissions still need to be investigated (8.1.6). Marginal shifts in freight volumes to rail and waterway can be achieved at relatively modest cost in public subsidies (Europe Economics, 2011). With and without these government incentives, many large corporations have committed to increasing their relative use of rail and / or barge services for a combination of economic, environmental and security reasons (Wright et al., 2010). Effecting a more radical shift to low carbon transport services, however, will probably require full internalisation of the environmental costs of freight transport incorporating a relatively high carbon price (Janic, 2007). Additional revenue raised to expand the capacity of rail and canal networks and facilitate intermodal transfer could reinforce the impact of this policy measure.

8.6.3 Energy intensity

Conventional passenger ICE vehicles could be continuously improved up to 2050 for a moderate price increase, to achieve close to a 50% increase in energy efficiency (Bandivadekar, 2008; EUCAR/CONCAWE/JRC, 2008; IEA, 2008). Net $CO_{2\text{-eq}}$ mitigation costs for advanced ICE vehicles[4] and HEVs are close to zero in the near term, and negative in the case of spark-ignition ICE hybrids and advanced spark-ignition ICEs in the long term (IEA, 2010d). PHEVs can deliver GHG savings at a cost between USD 140/$tCO_{2\text{-eq}}$ and USD 210 /$tCO_{2\text{-eq}}$ in the short term, reducing to USD 20/$tCO_{2\text{-eq}}$ in the best case (electricity from cheap hydropower), and up to USD 50/$tCO_{2\text{-eq}}$ using more expensive electricity in the long term. In regions with low cost and low-carbon renewable power generation, EVs with 150 km range could reach USD 80/$tCO_{2\text{-eq}}$ to USD 120/$tCO_{2\text{-eq}}$. In the same timeframe, FCV hybrids could achieve values close to USD 100/$tCO_{2\text{-eq}}$ if they use hydrogen produced from low-cost, low-carbon electricity, with a high cost of USD 190/$tCO_{2\text{-eq}}$ for more expensive hydrogen. All the above cost data vary with the assumptions on base vehicle performance, vehicle life, annual driving distance, fuel cost and discount rate.

In the US, medium and HDVs can achieve a reduction in fuel consumption per km of 38-51% between 2008 and 2020 (NRC, 2010b). The largest tractor-trailers could achieve around 50% reductions from a set of drive-train and vehicle technologies and logistical changes for about USD 85,000 per truck. For diesel fuel at USD0.66/l, a 3 year simple payback period results. However, potential fuel consumption reductions, capital costs, and breakeven diesel fuel prices vary for a range of HDVs.

If freight movement continues to rise sharply, the growth in related carbon emissions can be moderated by reducing the ratio of t-km to vehicle-km by improving the loading of freight vehicles and minimising their empty running (McKinnon and Ge, 2006). Under-utilisation of freight capacity is common across all transport modes and imposes a substantial economic as well as environmental cost. The potential also exists for companies to share transport capacity to a much greater degree on both a bilateral and multi-lateral basis (Pan et al., 2013), though this will require a change in corporate behaviour and, in some countries, a revision of competition law.

8.6.4 Fuel carbon intensity

Efforts to reduce the carbon dioxide intensity of transport have been largely unsuccessful, due to increased vehicle power and weight leaving average fuel economy constant (Millard-Ball and Schipper, 2011), despite the fact that diesel, with slightly lower CO_2 emissions per unit of transport service compared with gasoline (Tanaka et al., 2012), has been increasingly introduced in different markets and displaced the total fuel share of gasoline. Low-carbon biofuels and biomethane, as well as with electricity-based EVs for private use or public transport, are increasingly being deployed and future growth is expected (8.3) (IEA, 2009a, 2010d; Fischedick et al., 2011; Pacca and Moreira, 2011). Biofuels production costs vary across regions, raw materials, conversion processes, and final products. The cost of producing advanced biofuels tends to be higher than for first generation biofuels, even though delivered cellulosic feedstock costs per energy unit are usually lower than those of conventional feedstocks (Chum et al., 2011; Timilsina and Shrestha, 2011; REN21, 2012).

A summary of some mitigation costs and potentials is provided in Table 8.6.1.

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[4] These are the vehicles with better technologies such as improved engines, light-weighting, better aerodynamics and better tires than those for the current vehicles.

Table 8.6.1: Summary of costs and potentials for some examples for the transport sector

Mitigation options	**Potential GHG emission reduction(range)**	**Illustrative examples**	**Direct costs**	**Cost effectiveness**	**Key references**
Fuel carbon intensity: fuel switching					
1. Biofuels – sugar cane ethanol	0-80%	Commercial scale production in Brazil reach more than 80% reduction in fossil energy and CO2, apart from land use change effects	+/- 20% compared to gasoline	+/- USD$50/tonne	(IEA, 2011b)
2. Biofuels – ethanol from enzymatic hydrolysis	0-100%	Reaches 100% CO2 reduction (from full elimination of fossil inputs) in some test bed applications. Likely to be lower % at commercial scale. Possibly no savings if large land use change impacts	Currently up to USD$1.00/l higher production cost, projected to reach within USD$0.10/l (or less) of the cost of gasoline by 2030	Currently USD$500-1000/t, could drop to under USD50/t by 2030 in optimal circumstances	(IEA, 2011b) Bioenergy annex (chapter 11)
3. Biofuels - advanced biomass-to-liquids processes (gasoline/diesel drop-in replacement fuels)	0-100%	Reaches 100% CO2 reduction (from full elimination of fossil inputs) in some test bed applications. Likely to be lower % at commercial scale. Possibly 0 savings if large land use change impacts.	Currently up to USD$1.00/l higher production cost, projected to reach within USD$0.20/l (or less) of the cost of gasoline/diesel by 2030	Currently USD$500-1000/t, could drop to under USD$100/t by 2030 in optimal circumstances	(IEA, 2011b) Bioenergy annex (chapter 11)
4. Electricity	0-<100%				
Energy intensity: efficiency of technologies					
5. LDV efficiency	40-70% efficiency improvement by 2035 (IEA, 2012d) 50% improvements in vehicle fuel economy (MJ/km) by 2030-2035 compared to similar-sized, typical 2007-2010 vehicles	Toyota Yaris 2012 hybrid 79g/km CO2 vs. industry average 164g/km CO2 Drive-train redesigns of 25% or more (NRC, 2011a)	USD$2400-3000 for 50% improvement in 2020	Cost is negative, near – USD$150/ t with "base" assumptions	(Bandivadekar, 2008; ICCT, 2010; Greene and Plotkin, 2011; IEA, 2012a)
6. HDV efficiency	30-50% efficiency improvement by 2035 compared to 2007-2010	CO2 reduction due to block technologies of moderate (5%), expensive (10%), and very expensive (30%) Higher capacity vehicles may cut direct GHG emissions by up to 32%	Moderate(USD$6000), expensive(USD$23000), and very expensive(USD$45,000) Vehicle price increment USD$15,000-85,000		(ICCT, 2010; NRC, 2010b; IEA, 2012a)

7. Ships efficiency	Up to 60% CO2 reduction (750-1020 million t-CO2/yr) in 2030 compared to 2007	New builds 5-30%, retrofit and maintenance measures 2-20%; total 43% (2020) to 63% (2050) reduction of CO2 per t-km		Most measures: negative cost up to the reduction of 250 MtCO2/yr	(Crist, 2009; IMO, 2009; Notteboom and Vernimmen, 2009; ICCT, 2011b)
8. Aircraft efficiency	6-50%	Up to 50% efficiency improvement of new planes by 2035, 7-13% improvement for existing planes; A reduction in CO2 emissions of 50% by 2050, relative to 2005 levels.		USD$50/t-CO2: 20% reduction, USD$100/t-CO2: 30% reduction	(IATA, 2009)
9. Rail efficiency		EU target: reduction of specific CO2 emission by 50% (2030), and total CO2 emission level below 1990 level			(IEA and UIC, 2012)
10. Alternative propulsion	40-80%	Efficiency improvement of LDV; HEV 40-65%; FCV 70-75%; BEV 80%	Vehicle price increment USD$$4,000-22,000		
Structure: system infrastructure efficiency					
11. Long-distance rail infrastructure	8-40% , Direct CO2 intensity 12-19 gCO2/p-km	8% improvement via regenerative braking systems (Amtrak, US), 40% through design and engine improvements (Shinkansen, Japan)	USD$ 4-75 million /km		cf. 8.4.2.2 (UIC, 2011b; IEA, 2012d)
12. Mass rapid transit infrastructure	Direct CO2 intensity 3-21 gCO2/p-km		USD$ 27-330 million /km		cf. 8.4.2.2 (IEA, 2012d)
13. Light-rail transit infrastructure	Direct CO2 intensity 4-22 gCO2/p-km		USD$ 14-40 million /km		cf. 8.4.2.2 (IEA, 2012d)
14. Bus infrastructure	Direct CO2 intensity 14-22 gCO2/p-km for BRT 20-30% reduction in fuel consumption can be achieved via hybridisation	Bus Rapid Transit (BRT): USD$ 1-8 million /km of infrastructure New York City Transit obtained about 30% reduction in fuel consumption by using electric hybrid buses (Chandler et al., 2006).	USD$ 5-27 million /km:	USD$$15-70/t-CO2	cf. 8.4.2.2 (Chandler et al., 2006; IPCC, 2007; AEA, 2011; ITF, 2011; IEA, 2012d)
15. Non-motorised transit infrastructure		Walkable city, traffic calming, interconnected bicycle lanes			(Pucher and Buehler, 2008; Tight et al., 2011)

16. Information/ education	5-20%	HDV driver education 5-15% LDV eco-driving 5-10%			(IEA, 2012d)
17. Aviation (operational)	6-12% through traffic management and other operational improvements	Direct routings; flying at optimum altitudes and speeds; efficiency improvements of ground service equipment and auxiliary power units can deliver substantial efficiency gains			(Dell'Olmo and Lulli, 2003; Pyrialakou et al., 2012)
18. Maritime (operational)	Combined technical and operational measures have been estimated to potentially reduce CO2 emissions by up to 43% / t-km by 2020 and by up to 63% / t-km by 2050 (Crist, 2009). 25-75% reduction in GHG emission intensity by 2050 (IMO, 2009); 39-57% reduction 'attainable'; 59-72% 'optimistic' by 2050 (Lloyds Register and DNV, 2011)	Main operational measures yielding GHG savings: 'slow steaming' (cutting average vessel speed by 10% and 20% can cut GHG emissions by, respectively, 15-19% and 36-39% though allowance must be made for second order effects (e.g.need to increase fleet size plus increased trans-shipment); adjustments to trim and draft and weather routing (DNV, 2010).	Marginal abatement cost analysis distinguishes 'cost-effective' GHG reductions (marginal cost < 0) and reductions achievable within marginal cost of USD$100 / t of GHG saved	Combination of operational and technical measures: GHG reductions: with marginal cost < 0; 2020 24%; 2030 33%. with marginal cost <USD$100 / t GHG saved: 2020 35%; 2030 49%	(Crist, 2009; IMO, 2009; DNV, 2010; ICCT, 2011b; Lloyds Register and DNV, 2011; Eide et al., 2011)

19. Logistics operations	20%-27% reduction in GHG for range of eight transport-specific measures (clean vehicle technology, speed reduction, optimised logistics networks, training / communication, modal shift, near-shoring, increased home delivery, reduced congestion) - lower estimate based on feasibility weighting factors	Sources of CO2 reductions: clean vehicle technology (25%), speed reduction (24%), optimised logistics networks (24%), improved training and communication (16%), freight modal shift (14%) others (3%).	Estimates of capital costs relating to road freight operations; estimates of CO2e savings derived by averaging data; no data for costs of other measures	Low carbon technologies for urban and long haul road freight operations 12-19 kg CO2e life-time saving per Euro (2010) (equivalent to 9-15 kg CO2w per USD$ 2010); route management 4kg CO2e per Euro (equivalent to 3kg CO2e per USD$); driver training 14kg per Euro (equivalent to 11kg per USD$). UK Government advisory / best practice programme for freight / logistics £8 / t of CO2 saved (equivalent to USD$ 13 / t of CO2 saved)	(Lawson et al., 2007; TIAX, 2009; AEA, 2011; World Economic Forum, 2012)
Activity: demand reduction					
20. Densification of automobile-dependent suburbs	20-50% reduction in driving				(Ewing, 2007; Newman et al., 2009)
21. Behavioural change from reducing private motor vehicle use through pricing policies, eg network charges and parking fees.	0-30%				(TFL, 2007; Eliasson, 2008; Creutzig and He, 2009)
22. Behavioural change from education to encourage gaining benefits of less motor vehicle use.	Immediate impacts of 10-15% reduction of car use are possible.				(Goodwin and Lyons, 2010; Taylor and Philp, 2010; Ashton-Graham et al., 2011; Höjer, Dreborg, et al., 2011; Salter et al., 2011)(Pandey, 2006)

Table 8.6.2: Potential co-benefits (green) and risks (red) (case- and site-specific and depending on local circumstances as well as on the implementation practice) of selected mitigation options. (For possible upstream effects of low-carbon electricity, see Chapter 7. For possible upstream effects of biomass supply, see bioenergy annex to Chapter 11).

Transport sector mitigation options	**Non-climate benefits and risks**			
	Economic	**Social (including equity)**	**Environmental**	**Other**
Reducing fuel carbon intensity: e.g. by electrification, biofuels, CNG and other measures.	Transport affordability for businesses (some measures may increase freight transport costs) (see Section 8.6) Energy security (reduction of oil dependency) (1,2) Terms of trade for oil-importing countries by increasing the costs of production (3)	Lower exposure to oil price volatility risks (1,2) Noise reduction (via electrification and fuel cells) (10)	Electrification, hydrogen: Health and ecosystem benefits due to potential large reductions of local urban air pollution from many key pollutants (13,20) CNG, biofuels: Health and ecosystem benefits are uncertain (19,20)	Resource risk (e.g. limited supply of battery of fuel cell material inputs) (17,18)
Reduction of energy intensity	Transport affordability for businesses (4,5) Energy security (1,2)	Transport affordability for households (lower travel costs for the consumer due to improved engine and vehicle performance efficiency. Under some circumstances, can increase travel costs for the consumer) (1,2)	Health and ecosystem benefits due to reduced urban air pollution (20)	
Improve urban form and infrastructure. Modal shifts (e.g. from private to public transport or non-motorised modes)	Improved productivity due to reduced urban congestion and travel times across all modes (6,7) Energy security (1,2)	More equitable mobility access and safety, particularly in developing countries (8) Potentially reduced risks of accidents by provision of safer transport (mainly modal shift) and infrastructure for pedestrians and cyclists (7,11)	Health and ecosystem benefits due to (i) reduced urban air pollution and (ii) reduced exposures to air pollution (7,20) Health benefits from shifts to active transport modes (7,12)	
Journey reduction and avoidance	Improved productivity due to reduced urban congestion and travel times (6,7) Energy security (1,2) Freight deliveries avoiding need to collect (14)	Improved access and mobility (9)	Health and ecosystem benefits due to reduced urban air pollution (20) Reduced land-use from transport infrastructure (7, 9) Potential risk of damages to vulnerable ecosystems from shifts to new and shorter routes (15,16)	

References: 1: (Greene, 2010b); 2: (Costantini et al., 2007); 3:(Kaufmann, R.K., Dees, S., Karadeloglou, P., Sánchez, 2004a); 4: (Boschmann, 2011); 5: (Sietchiping et al., 2012); 6: (Cuenot et al., 2012); 7: (Creutzig et al., 2012a); 8: (Banister, 2008a); 9: (Geurs and Van Wee, 2004; Banister, 2008b); 10: (Creutzig and He, 2009); 11: (Tiwari and Jain, 2012a); 12: (Rojas-Rueda et al., 2011); 13: (Sathaye et al., 2011); 14: (Olsson and Woxenius, 2012); 15: (Garneau et al., 2009); 16: (Wassmann, 2011); 17: Eliseeva and Bünzli 2011; 18: Massari and Ruberti 2013; 19: (Takeshita, 2012a); 20: (Kahn Ribeiro et al., 2012).

8.7 Co-benefits, risks and spill-overs

Mitigating climate change in the transport sector can generate synergies and co-benefits, but also trade-offs and spill-overs with related risks and uncertainties. Transport relies almost entirely on a single fossil fuel resource with about 94% of transport fuels being petroleum products (IEA, 2011a). This makes it a key area of energy security concerns. It is also a major source of harmful emissions, which affects air quality in urban areas (8.2). Public health, road safety and traffic congestion are crucial co-dimensions possibly influenced by mitigation actions (Bongardt et al., 2013).

FAQ 8.3: Are there any co-benefits associated with mitigation actions in the Transport Sector?

Yes, there are many co-benefits associated with mitigation actions in the transport sector. These actions may be associated with broader transport policies and programs that usually target several policy objectives, with positive impacts on travel costs and mobility, improved health and reduced local air pollution, reduction in traffic congestion, energy security and potentially road safety. A number of studies suggest that the direct and indirect benefits of sustainable transport measures often exceed the costs of their implementation. However, the quantification of co-benefits and the associated welfare effects remains challenging.

8.7.2 Socio economic, environmental and public health co-benefits

In scenario studies of European cities, a combination of public transit and cycling infrastructures, pricing and land-use measures is projected to lead to notable co-benefits in energy security, savings from fuel spending, less congestion, increased public health (more physical activity, less air pollution, less noise-related stress) and fewer accidents (Creutzig et al., 2012b). However, only a few studies have assessed social costs and co-benefits comprehensively and these are hampered by data uncertainties. Even more fundamental is the epistemological uncertainty attributed to different social costs. As a result, the range of plausible social costs and benefits can be large. For example, the social costs of the co-dimensions congestion, air pollution, accidents, and noise in Beijing were assessed to equate to between 7.5% to 15% of GDP (Creutzig and He, 2009).

Energy security. Transport stands out in comparison to other energy end-use sectors due to its almost complete dependence on petroleum products. Transport has been identified as the most vulnerable energy system from a security standpoint (Cherp et al., 2012). No other energy consuming sector is less diversified than transport (Sorrell and Speirs, 2009) (8.2). This reliance and the resulting high and volatile oil prices affect disposable incomes, reduce the terms of trade for oil-importing countries and raise inflation by increasing the costs of production (Kaufmann, R.K., Dees, S., Karadeloglou, P., Sánchez, 2004b). The large majority of the world's population lives in countries, including almost all low-income countries, which rely on imported oil and oil products for their transport sector (Cherp et al., 2012). At the same time, global oil resources are increasingly concentrated in just a few regions. The transport sector is also especially vulnerable from the resilience perspective because there are no easily available substitutes to oil and oil products in case of their potential disruption. Finally, from a robustness perspective, the demand for transport fuels is rapidly growing in many developing countries whereas the global oil resources are widely perceived as scarce. The combination of growing demand and perceived scarcity of resources leads to energy security anxieties and potentially tensions between nations (Cherp and Jewell, 2011).Transport energy efficiency gains will directly affect the sector’s dependence on fossil fuel products and contribute to improved energy security (Leiby, 2007; Shakya and Shrestha, 2011).

Access, mobility and affordability. Mitigation strategies that foster multi-modality are likely to foster improved access to transport services particularly for the poorest and most vulnerable members of society. Improved mobility usually helps provide access to jobs, markets and facilities such as hospitals and schools (Banister, 2011b; Boschmann, 2011; Sietchiping et al., 2012). More efficient transport and modal choice not only increases access and mobility it also positively affects transport affordability (Banister, 2011b). Transport systems that are affordable and accessible foster economic efficiency and social inclusion (Banister, 2008a; Miranda and Rodrigues da Silva, 2012).

Traffic congestion. Some transport mitigation actions can also reduce traffic congestion. These include congestion pricing and modal shifts from aviation to rail and from LDVs in cities to public transport, walking and cycling (Cuenot et al., 2012); (Creutzig et al., 2012b). Others may even create adverse rebound effects of increased traffic generated by expansion of airport infrastructure or construction of roads to temporarily relieve congestion (Goodwin, 2004; ECMT, 2007; Small and van Dender, 2007).

Congestion is an important aspect for decision makers, in particular at the local level, as it negatively affects journey times and creates substantial economic cost (Goodwin, 2004; Duranton and Turner, 2011). For example, in the US in 2000, time lost in traffic amounted to around 0.7% of GDP (Federal Highway Administration, 2000) or US$79 billion which increased to US$101 billion in 2010, also being 0.7% of GDP but with more accurate data covering the cost per kilometre travelled of each major vehicle type for 500 urban centres (Schrank et al., 2011). In the UK, time lost was valued at 1.2% of GDP (Goodwin, 2004); 3.4% in Dakar, Senegal and 4% in Manila, Philippines (Carisma and Lowder, 2007); 3.3% to 5.3% in Beijing, China (Creutzig and He, 2009); 1% to 6% in Bangkok, Thailand (World Bank, 2002) and up to 10% in Lima, Peru where people on average spend around four hours in daily travel (JICA, 2005; Kunieda and Gauthier, 2007).

Air quality, physical activity and public health*.* Transport contributes to global GHG emissions but also to local air pollution, noise and vibration issues (WHO, 2008). City-scale environmental impact assessments are likely to be strengthened as a number of potentially significant climate change impacts are either unique to urban areas or exacerbated in them (Lindley et al., 2006). Exposure to vehicle exhaust emissions mostly in the form of sulphur oxides (SOx), nitrous oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), volatile organic compounds (VOC), toxic metals, lead particles and particulate matter (PM) (8.2) can cause cardiovascular, pulmonary, respiratory diseases and several other negative health impacts (WHO, 2008). In Beijing, for example, the social costs of air pollution are estimated to be as high as those from congestion time delays (Creutzig and He, 2009).

Transport-related inactivity has been linked to several chronic diseases (WHO, 2008). An increase in walking and cycling activities could therefore lead to health benefits but conversely, may also lead to an increase in traffic accidents and a larger lung intake of air pollutants. However, overall, the benefits of cycling and walking significantly outweigh the risks (Rojas-Rueda et al., 2011; Rabl and de Nazelle, 2012).

Assessing the social cost of public health is a highly contested area when presented as disability-adjusted life years (DALYs). A reduction in CO_2 emissions through an increase in active travel and less use of ICE vehicles had larger associated health benefits in London (7 332 DALYs per million population per year) and Delhi (12,516 DALYs /million/yr) than from the increased use of lower-emission vehicles (160 DALYs/million/yr in London, and 1,696 in Delhi) (Woodcock, Edwards, Tonne, Armstrong, Ashiru, Banister, Beevers, Chalabi, Chowdhury, Cohen, et al., 2009). In a similar trend, reduced car use in Australian cities has been shown to reduce health costs and improve productivity due to an increase in walking (Trubka et al., 2010a; b; c).

Strategies that target local air pollution also show potential to reduce GHG emissions (Yedla et al., 2005) and black carbon emissions (UNEP and WMO, 2011). In designing mitigation measures to reduce specific pollutants, GHG emissions reductions can also occur (8.2).

Road transport safety. The increase in motorised traffic in most countries places an increasing incidence of road accidents with 1.27 million people killed each year, of which 91% occur in low and middle-income countries (WHO, 2011). A further 20 to 50 million people suffer serious injuries (WHO, 2011). By 2030, it is estimated that road traffic injuries will constitute the fifth biggest reason for premature deaths (WHO, 2008). Measures to increase the efficiency of the vehicle fleet can also positively affect the crash-worthiness of the vehicle fleet if more stringent safety standards are adopted along with improved efficiency standards (Santos et al., 2010).

8.7.3 Technological risk trade-offs and uncertainties

There are a number of technological risks and uncertainties associated with different de-carbonization strategies for transport. Fuel carbon intensity and energy intensity technology mitigation options are particularly affected by risks and uncertainties regarding the technological viability and life-cycle emission reduction potential (8.3). However, mitigation options more generally are also likely to be subject to rebound effects to varying degrees (8.10).

Biofuels are a good example when it comes to uncertainties and risks of mitigation options (8.3 and Chapter 11, Bioenergy Annex). To evaluate the risks and uncertainties, criteria are being developed to ensure a degree of sustainability in their production and use (Chum et al., 2011)). Regulations and sustainability criteria and indicators try to ensure that adverse impacts are avoided (Larsen et al., 2009). Although certification approaches have been scrutinized and challenged (Franco et al., 2010), initial data on monitoring sustainability certification of bioenergy is starting to emerge through surveys of more than 200 stakeholders, including a wide range of schemes with recommendations on improvements for sustainability of certified markets so it can support the development of tradable commodities (IEA, 2011b).

A focus on improving vehicle fuel efficiency may reduce GHG emissions and potentially improve air quality, but without an increase in modal choice, it may not result in improved access and mobility (Steg and Gifford, 2005). The shift toward more efficient vehicles in many European countries has also created trade-offs which can negatively affect air quality in cities (Kirchstetter et al., 2008).

8.7.4 Social acceptability

The acceptance of measures to reduce GHG emissions is fostered by their ability to generate co-benefits and avoid trade-offs (Zusman et al., 2012) (Miola, 2008). Focusing on other objectives and integrating them with climate change mitigation as a co-benefit is hence a very practical way of ensuring the acceptance of low-carbon transport policies (Schipper et al., 2010). Campaigns to raise public awareness and foster acceptability are widely used measures to boost walking and cycling and public transport (Davies, 2012). Different transport modes experience different levels of social acceptability and views may be influenced by age, gender, social and economic backgrounds, car ownership, and region (Goodwin and Lyons, 2010). Acceptability depends upon the introduction of pricing measures (most typically road pricing), alternatives to investments for car-based passenger transport, new technologies and fuels (Pridmore and Miola, 2011) and regulations.

The continuing growth of shipping and aviation with related air pollution indicates that these sectors may increasingly become areas of future scrutiny (Morton et al., 2011). Proposals to build new airports are already becoming controversial (May and Hill, 2006).

Although freight transport typically accounts for only a small share of total transport emissions (Carbon Trust, 2006), a shift in consumer demand to low carbon products would also result in the adoption of co-benefits (Upham et al., 2011). Many carbon-reduction measures applicable to the freight sector, such as the modal switch from road to rail, more localised sourcing of products and electrification of the commercial LDV fleet, have high social acceptability, mainly because of their co-beneficial effects on air quality and traffic congestion (TNS/BMRB, 2010). Increasing truck size permits the movement of road freight in larger, more energy-efficient loads but can meet with public resistance (Knight et al., 2008). Once implemented however, higher HDV size and weight limits could overcome psychological barriers (8.8) and gain rapid acceptance (Davydenko et al., 2010).

8.8 Barriers and opportunities

Barriers and opportunities are processes that hinder or facilitate deployment of new transport technologies and practices as outlined in this chapter. Reducing transport GHG is inherently complex as increasing mobility with LDVs, HDVs and aircraft has been associated with increasing wealth for the past century of industrialisation (Meyer et al., 1965; Glaeser, 2011). The first signs of decoupling fossil fuel-based mobility from wealth generation may be appearing in OECD countries. To reduce GHG emissions, a range of technologies and practices have been identified that are likely to be developed in the short- and long-terms (8.3), but barriers to their deployment exist as do opportunities for those nations, cities and regions willing to make low carbon transport a priority. There are many barriers to implementing a significantly lower carbon transport system, but these can be turned into opportunities if sufficient consideration is given and best-practice examples are followed.

8.8.1 Barriers and opportunities to reduce GHGs by technologies and practices

The key transport-related technologies and practices garnered from sections above are set out in terms of their impact on fuel carbon intensity, improved energy intensity of technologies, system infrastructure efficiency, and transport demand reduction. Each has short- and long-term potentials to reduce transport GHG emissions which can then be assessed in terms of their barriers and opportunities (Table 8.8.1). (Details of policies follow in Section 8.10).

Psychological barriers also exist. These can impede behavioural choices that might otherwise facilitate mitigation, adaptation, and environmental sustainability. Although many individuals are engaged in ameliorative actions to improve their local environment, most people could do more but are hindered by psychological barriers. These include limited cognition about the problem, ideological worldviews that tend to preclude pro-environmental attitudes and behaviour, comparisons with the responses of other people, sunk costs and behavioural momentum, a dis-credence toward experts and authorities, perceived risks as a result of making change,; and positive but inadequate confidence to make behavioural change (Gifford, 2011).

Table 8.8.1 Transport technologies and practices with potential for both short- and long-term GHG reduction and the related barriers and opportunities in terms of the policy arenas of fuel carbon intensity, energy intensity, infrastructure and activity.

Transport technology or practice	Short-term possibilities	Long-term possibilities	Barriers	Opportunities	References
Fuel carbon intensity: fuel switching	PEV – Plug-in electric vehicle; PHEV – Plug-in hybrid electric vehicle; FCV – Fuel cell vehicles CNG – Compressed natural gas; LNG – Liquefied natural gas; CBG – Compressed biogas; LBG – Liquefied biogas				
1. PEVs and PHEVs based on renewable electricity.	Rapid increase in use likely over next decade from a small base, so only a small impact likely in short-term	Significant replacement of ICE-powered LDVs.	EV and battery costs reducing but still high. Lack of infrastructure, and recharging standards not uniform. Vehicle range perceptions between recharging. Lack of capital and electricity in some least developed countries.	Universal standards adopted for rechargers. Demonstration green city areas with plug-in infrastructure. Decarbonised electricity. Smart grids based on renewables. EV subsidies. New business models, such as community car sharing.	(EPRI, 2008; Beck, 2009; IEA, 2011c; Salter et al., 2011; Kley et al., 2011; Leurent and Windisch, 2011; Graham-Rowe et al., 2012)
2. CNG, LNG, CBG and LBG displacing gasoline in LDVs and diesel in HDVs.	Infrastructure available in some cities so can allow a quick ramp–up of gas vehicles in these cities.	Significant replacement of HDV diesel use depends on ease of engine conversion, fuel prices and extent of infrastructure.	Insufficient government programmes, conversion subsidies and local gas infrastructure and markets. Leakage of gas.	Demonstration gas conversion programmes that show cost and health co-benefits. Fixing gas leakage in general.	(IEA, 2007; Salter et al., 2011; Alvarez et al., 2012)
3. Biofuels displacing gasoline, diesel and aviation fuel.	Niche markets continue for first generation biofuels (3% of liquid fuel market, small biogas niche markets).	Advanced and drop-in biofuels likely to be adopted around 2020-2030, mainly for aviation.	Some biofuels can be relatively expensive, environmentally poor and cause inequalities by impacting on food prices.	Drop-in fuels attractive for all vehicles. Biofuels and bio-electricity can be produced together, e.g. sugarcane ethanol and CHP from bagasse. New biofuel options need to be further tested, particularly for aviation applications.	(Ogden et al., 2004; Fargione et al., 2010; IEA, 2010b; Plevin et al., 2010; Creutzig, Popp, et al., 2011; Salter et al., 2011; Pacca and Moreira, 2011) (Flannery et al., 2012)
Energy intensity: efficiency of technologies	FEV – fuel efficient vehicles				

4. Improved vehicle internal combustion engine technologies and on-board information and communication technologies (ICT) in fuel efficient vehicles.	Continuing fuel efficiency improvements across new vehicles of all types can show large, low-cost, near-term reductions in fuel demand.	Likely to be a significant source of reduction. Behavioural issues (e.g. rebound effect). Consumer choices can reduce vehicle efficiency gains.	Insufficient regulatory support for vehicle emissions standards. On-road performance deteriorates compared with laboratory tests.	Creative regulations that enable quick changes to occur without excessive costs on emissions standards. China and most OECD countries have implemented standards. Reduced registration tax can be implemented for low CO_2e-based vehicles.	(Schipper et al., 2000; Ogden et al., 2004; Small and van Dender, 2007; Sperling and Gordon, 2009; Timilsina and Dulal, 2009; Fuglestvedt et al., 2009b; Mikler, 2010; Salter et al., 2011)
Structure: system infrastructure efficiency					
5. Modal shift by public transport displacing private motor vehicle use.	Rapid short-term growth already happening.	Significant displacement only where quality system infrastructure and services are provided.	Availability of rail, bus, ferry and other quality transit options. Density of people to allow more access to services. Levels of services. Time barriers on roads without right of way Public perceptions.	Investment in quality transit infrastructure, density of adjacent land use and high level of services using innovative financing that builds in these features. Multiple co-benefits especially where walkability health benefits are a focus.	(Kenworthy, 2008; Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011a; Salter et al., 2011; Buehler and Pucher, 2011; Newman and Matan, 2013b)
6. Modal shift by cycling displacing private motor vehicle use.	Rapid short term growth already happening in many cities.	Significant displacement only where quality system infrastructure is provided.	Cultural barriers and lack of safe cycling infrastructure and regulations. Reasonable climate.	Demonstrations of quality cycling infrastructure including cultural programmes and bike sharing schemes.	(Bassett et al., 2008a; Garrard et al., 2008; Salter et al., 2011; *City cycling*, 2012; Sugiyama et al., 2012)
7. Modal shift by walking displacing private motor vehicle use.	Some growth but depends on urban planning and design policies being implemented.	Significant displacement where large-scale adoption of polycentric city policies and walkable urban designs are implemented.	Planning and design policies can work against walkability of a city by too easily allowing cars into walking city areas. Lack of density and integration with transit. Culture of walkability.	Large scale adoption of polycentric city policies and walkable urban designs creating walking city in historic centres and new ones. Cultural programmes.	(Gehl, 2011; Höjer, Gullberg, et al., 2011; Leather et al., 2011; Salter et al., 2011)

8. Urban planning by reducing the distances to travel within urban areas.	Immediate impacts where dense transit-oriented development (TOD) centres are built.	Significant reductions where widespread polycentric city policies are implemented.	Urban development does not always favour dense TOD centres being built. TODs need quality transit at their base.	Widespread polycentric city policies implemented with green TODs, backed by quality transit. Multiple co-benefits in sprawl costs avoided and health gains.	(*The new transit town*, 2004, *Transit oriented development*, 2009; Naess, 2006; Ewing et al., 2008; Cervero and Murakami, 2009, 2010; Cervero and Sullivan, 2011; Salter et al., 2011) (Lefèvre, 2009)
9. Urban planning by reducing private motor vehicle use through parking and traffic restraint.	Immediate impacts on traffic density observed.	Significant reductions only where quality transport alternatives are available.	Political barriers due to perceived public opposition to increased costs, traffic and parking restrictions. Parking codes too prescriptive for areas suited to walking and transit.	Demonstrations of better transport outcomes from combinations of traffic restraint, parking and new transit /walking infrastructure investment.	(Gwilliam, 2003; ADB, 2011b; Creutzig, McGlynn, et al., 2011; Shoup, 2011; Newman and Matan, 2013a)
10. Modal shift by displacing aircraft and LDV trips through high-speed rail alternatives.	Immediate impacts after building rail infrastructure.	Continued growth but only short-medium distance trips suitable.	High-speed rail infrastructure expensive.	Demonstrations of how to build quality fast-rail using innovative finance.	(Park and Ha, 2006; Gilbert and Perl, 2010; Åkerman, 2011a; Salter et al., 2011)
11. Modal shift of freight by displacing HDV demand with rail.	Suitable immediately for medium- and long-distance freight and port traffic.	Substantial displacement only if large rail infrastructure improvements made, the external costs of freight transport are fully internalised and the quality of rail services are enhanced. EU target to have 30% of freight tonne-km moving more than 300km to go by rail (or water) by 2030.	Inadequacies in rail infrastructure and service quality. Much freight moved over distances that are too short for rail to be competitive.	. Upgrading of intermodal facilities. Electrification of rail freight services. Worsening traffic congestion on road networks and higher fuel cost will favour rail.	(IEA, 2009b; Schiller et al., 2010; Salter et al., 2011)
12. Modal shift by displacing truck and car use through waterborne transport.	Niche options already available. EU Motorways of the Sea programme demonstrates potential to expand short-sea shipping share of freight market.	Potential to develop beyond current niches, though will require significant investment in new vessels and port facilities.	Lack of vision for water transport options and land-locked population centres. Long transit times. Tightening controls on dirty bunker fuel and SOx and NOx emissions raising cost and reducing modal competitiveness.	Demonstrations of quality waterborne transport that can be faster and with lower-carbon emissions than alternatives.	(Fuglestvedt et al., 2009b; Salter et al., 2011)

13. System optimization by improved freight logistics and efficiency at airports to reduce delays on runways and ports to improve logistics of ship and truck movements.	Continuing improvements showing immediate impacts.	Insufficient in long term to significantly reduce carbon emissions without changing mode, reducing mobility or reducing fuel carbon intensity.	Insufficient regulatory support and key performance indicators (KPIs) covering logistics and efficiency.	Creative regulations and KPIs that enable change to occur rapidly without excessive costs.	(Pels and Verhoef, 2004; Zhang and Zhang, 2006; Fuglestvedt et al., 2009b; Kaluza et al., 2010; McKinnon, 2010; Simaiakis and Balakrishnan, 2010; Salter et al., 2011)
Activity: demand reduction					
14. Mobility service substitution by reducing the need to travel through enhanced communications.	Niche markets growing and ICT improving in quality and reliability.	Significant reductions possible after faster broadband and quality images available, though ICT may increase the need for some trips.	Technological barriers due to insufficient broadband in some regions.	Demonstrations of improved video-conferencing system quality.	(Golob and Regan, 2001; Choo et al., 2005; Wang and Law, 2007; Yi and Thomas, 2007; Zhen et al., 2009; Salter et al., 2011) (Mokhtarian and Meenakshisundaram, 2002)
15. Behavioural change from reducing private motor vehicle use through pricing policies, eg network charges and parking fees.	Immediate impacts on traffic density observed.	Significant reductions only where quality transport alternatives are available.	Political barriers due to perceived public opposition to increased pricing costs.	Demonstrations of better transport outcomes from combinations of pricing, traffic restraint, parking and new infrastructure investment from the revenue.	(Litman, 2005, 2006; Creutzig, McGlynn, et al., 2011; Salter et al., 2011)
16. Behavioural change from education to encourage gaining benefits of less motor vehicle use.	Immediate impacts of 10-15% reduction of car use are possible.	Significant reductions only where quality transport alternatives are available.	Lack of belief by politicians and professionals in the value of educational behaviour change programmes.	Demonstrations of 'travel smart' programmes linked to improvements in sustainable transport infrastructure. Cost effective and multiple co-benefits.	(Pandey, 2006; Goodwin and Lyons, 2010; Taylor and Philp, 2010; Ashton-Graham et al., 2011; Höjer, Gullberg, et al., 2011; Salter et al., 2011)

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The range of barriers to the ready adoption of the above technologies and practices have been described in previous sections but are summarised in Table 8.8.1 along with the opportunities available. The challenges involved in removing barriers in each of the 16 elements listed depend on the politics of a region. In most places, reducing fuel carbon and energy intensities are likely to be relatively easy as they are technology-based, though they can meet capital investment barriers in developing regions and may be insufficient in the longer-term. On the other hand, system infrastructure efficiency and transport demand reduction options would require human interventions and social change as well as public investment. Although these may not require as much capital investment, they would still require public acceptance of any transport policy option (8.10). As implementation approaches, public acceptance fluctuates, so can require political support at critical times (Pridmore and Miola, 2011).

8.8.2 Financing low-carbon transport

Transport is a foundation for any economy as it enables people to be linked, goods to be exchanged, and cities to be structured (Glaeser, 2011). Transport is critical for poverty reduction and growth in the plans of most regions, nations and cities and therefore is a key area to receive development funding. In past decades the amount of funding going to transport through various low-carbon mechanisms has been relatively low, but with a recent increase. The UNEP pipeline database for clean development mechanism (CDM) eligible projects shows only 42 CDM projects out of 9064 have been transport-related representing 0.05% of all certified emission reduction units (Kopp, 2012). The Global Environment Facility (GEF) has approved only 28 projects in 20 years, and the World Bank's Clean Technology Fund has funded transport projects for less than 17% of the total. If this international funding does not improve, then transport could move from emitting 22% of energy-related GHGs in 2009 to reach 80% by 2050 (ADB, 2012b). Conversely national appropriate mitigation measures (NAMAs) could attract low-carbon financing in the transport area for the developing world with regional banks pledging to invest $175 billion for the creation of sustainable transport systems worldwide (Chapter 16, (Marton-Lefèvre, 2012).

A major part of funding sustainable transport could arise from the redirection of funding from unsustainable transport (UNEP, 2011; ADB, 2012a) and from most transport-related NGOs (Sakamoto et al., 2010). In addition, there are new mechanisms being developed to assist cities in all parts of the world to find capital investment to support mass transit. For example, in locations close to a new rail system, revenue can be generated from land-based taxes and rates that are seen to rise by 20-50% compared to areas not adjacent to such an accessible facility (Cervero, 1994; Haider and Miller, 2000; Rybeck, 2004). A number of value capture projects are underway in Indian cities (McIntosh and Newman, 2012). The ability to fully outline the costs and benefits of low-carbon transport projects will be critical to accessing these new funding opportunities. R&D barriers and opportunities exist for all of these agendas in transport.

8.8.3 Institutional, cultural and legal barriers and opportunities

Institutional barriers to low-carbon transport include international standards required for new EV infrastructure to enable recharging; low pricing of parking; lack of educational programmes for modal shift; and polycentric planning policies that require the necessary institutional structures (OECD, 2012). Cultural barriers underlie every aspect of transport, as, for example, automobile dependence being built into a culture and legal barriers can exist to prevent the building of dense, mixed-use community centres that reduce car dependence. Overall, there are political barriers which combine most of the above (Pridmore and Miola, 2011).

Opportunities also exist. The new "Sixth Wave" world economy (Hargroves and Smith, 2008) and green growth programmes (OECD, 2011) aim to depend on low-carbon emission technologies and practices. Transport elements are likely to be the basis of this changing economy because they shape cities and create wealth (Newman and Kenworthy, 1999; Glaeser, 2011). Those nations, cities, businesses and communities that grasp the opportunities to demonstrate these changes are likely to be the ones that benefit most in the future (OECD, 2012). The process of decoupling economic growth from fossil fuel dependence is a major feature of the future economy (ADB, 2012b) with sustainable transport being one of four key approaches. The barriers to, and opportunities for, each technology and practice (Table 8.8.1) show that each can contribute to a more sustainable transport system and all are needed to enable the opportunities from technological and social changes that underlie the green economy to be gained.

8.9 Sectoral implication of transformation pathways and sustainable development

Results from integrated assessment models (IAMs) (Chapter 6) show that directed measures can reduce GHG emissions substantially from the transport sector (8.9.1). Diverse transformational pathways for a low-carbon global transport system can be envisioned through new and existing technologies for fuels and vehicles, and a progressive reconfiguration of structural components (8.9.2). Building on technical developments and spatial restructuring, the long-term economic, environmental and social impacts of these transitions need to be addressed systemically and communicated to the appropriate stakeholders. Any possible transition is subject to institutional and social acceptability, which is a function of time evolution, comparative costs and regional context variations (8.9.3).

8.9.1 Sectoral transformations and the long term stabilization goals

The assessment of the scenario database on transformation pathways for the transport sector from global energy-economy and integrated assessment models (6.7) gave a range of global CO_2 emission estimates based on a mix of fuel energy carriers and total final energy uses (Fig. 8.9.1). Projections vary greatly depending on future actions taken. If current trends in travel demand continue (8.1) and technological (8.3), infrastructural (8.4), educational and other systemic opportunities are not seized, then transport-related carbon emissions could increase by almost fourfold by the end of this century. If, however, emission reduction polices (8.10) and available technical and social options (8.3, 8.4 and 8.6) are realized, the sector could reduce its emissions substantially. The ranges calculated from the scenarios are large, indicating high uncertainty. Despite this, top-down scenarios demonstrate that atmospheric stabilisation at 450 ppm CO_2 by 2100 will rely heavily on transport sector mitigation. These top-down model insights are compared with specific transport models (8.9.2) and regional and sustainable development implications also discussed (8.9.3).

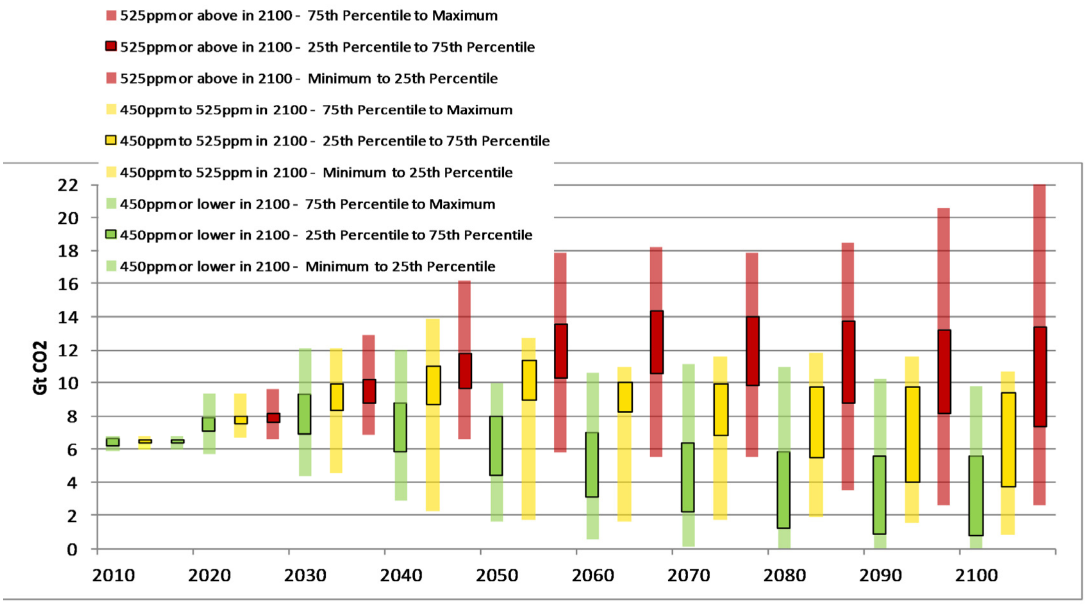

Figure 8.9.1. Direct global CO_2 emissions from transport based on a comparison of several integrated assessment models that give different levels of CO_2 concentrations by 2100 (Source: AR5 Scenario Database).

Activity. In the long-term, demand for passenger travel increases in all models/scenarios (Fig. 8.9.2a). Regions and countries will need to implement strong measures to achieve the CO_2 emission reductions (Fig. 8.9.1) because the benefits of current policies could be quickly offset with the expected global growth (McCollum and Yang, 2009; Huo et al., 2011; Harvey, 2012; Girod et al., 2012) . Passenger and freight activity increases are mostly driven by income growth, positive income elasticity and the relative price-inelastic nature of the passenger transport sector (Dargay, 2007; Barla et al., 2009), although some models project a decoupling from GDP by the end of this century (Girod et al., 2012).

Future activity in freight transport (Fig 8.9.2b) indicates that more stringent mitigation goals could lead to stabilization or even peak emissions that decrease in the long-term. The potential for decoupling freight transport from GDP seems to be strong although the ranges for freight activity are significantly larger than those for passenger transport. Freight transport demand has historically been closely coupled to GDP. While there has been evidence of decoupling in countries such as Finland (Tapio, 2005), the UK (McKinnon, 2007) and Denmark (Kveiborg and Fosgerau, 2007), there is limited evidence of such decoupling elsewhere. Where it does occur it is partly associated with the displacement of economic activity to other countries. Pronounced decoupling could result from a return to more localised sourcing, a major shift in the pattern of consumption to services and products of higher value density, the digitisation of media- and entertainment, extensive application of new transport-reducing manufacturing technologies such as 3D printing and the substitution of fossil fuels by renewable and nuclear energy. Uncertainty about the rate and extent of these developments is reflected in the degree of uncertainty in long-term freight modelling (Girod et al., 2012) and the IAM freight scenario outputs. Not all IAMs included transport activity. Therefore, this analysis is based on a smaller sample of models/scenarios.

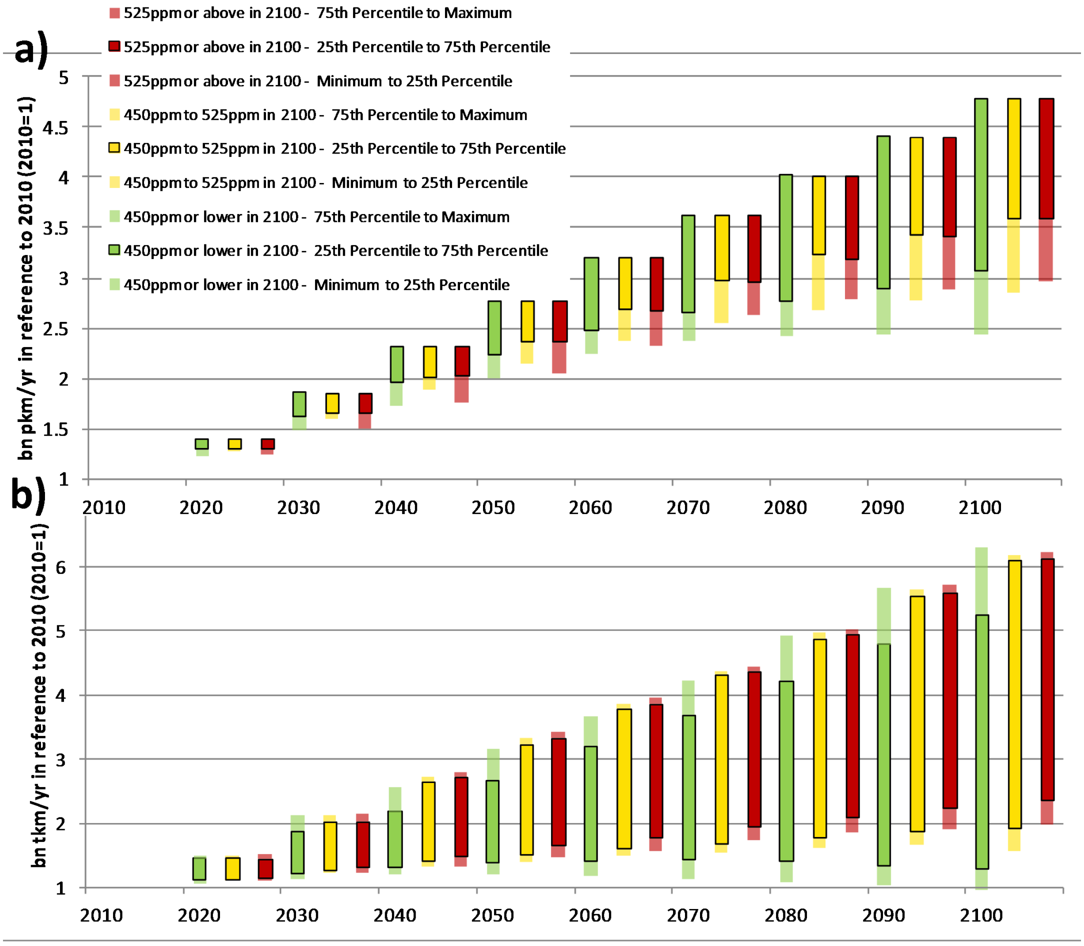

Figure 8.9.2: Global passenger (a) and freight (b) demand projections out to 2100 based on integrated assessment models with various levels of CO_2 concentrations. Values have been normalized (2010=1) given the uncertainty in base year values across different models (Source: AR5 Scenario Database).

Energy intensity. To achieve stabilisation targets, accelerated technical innovation is required in all areas of passenger and freight transport and related-infrastructure over the course of this century. Passenger transport is expected to become more efficient in terms of the energy spent for a given mobility service (Fig. 8.9.3a). Improved vehicle fuel efficiency, smarter systems, improved traffic flows and better driving practices play an important role in stabilization goals in all transition pathways.

A greater level of uncertainty exists on the future development of energy intensity for freight transport (Fig. 8.9.3b). A slowing growth in activity (Fig. 8.9.2b) and greater decarbonization of energy supply result from more stringent stabilization goals accompanied by improvements in freight transport efficiency. The energy intensity of freight movement can be substantially reduced by a combination of improved vehicle utilisation, the load consolidation in larger vehicles and vessels, modal switch to rail and waterborne transport and operational and technological improvements in fuel efficiency (IEA, 2009b; McKinnon and Piecyk, 2009; Sorrell et al., 2012). Less stringent goals would still lead to improvements in energy efficiency, even in models with lower reductions in transport demand and fuel switching.

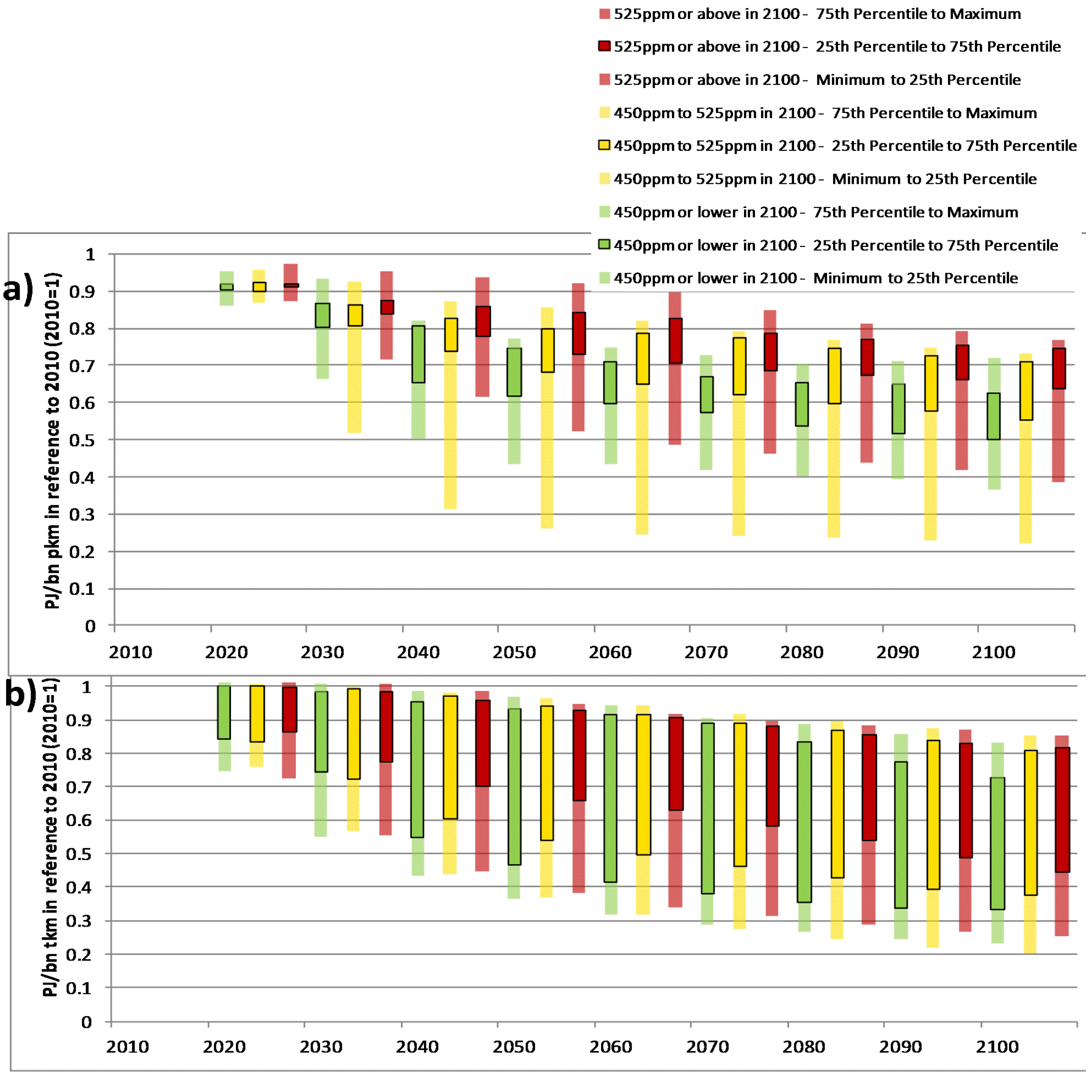

Figure 8.9.3 Energy intensity scenarios for passenger (a) and freight (b) transport out to 2100 based on integrated assessment models with various levels of CO_2 concentrations. Values have been normalized (2010=1) given uncertainty in base year values across different models (Source: AR5 Scenario Database).

Structure. The increase in travel demand will mostly take place within the road and aviation sub-sectors, driven *inter alia* by income (8.2) and demonstrating the inertia of the related transport infrastructure system (IEA, 2009b, 2012d; Kahn Ribeiro et al., 2012; Schuckmann et al., 2012). Aviation and road transport have much higher energy intensity than other modes (buses, trains and boats). Therefore, they account for a larger share of emissions than their share of service demand (Girod et al., 2012). The share of emissions from aviation tends to increase although limited data is available to assess changes in modal structure as not all IAMs provided information at such a disaggregated level.

Fuel carbon intensity. Fuel switching plays a major role in more stringent stabilization goals, leading to practically zero direct carbon intensity of the fuels used for all transport modes in 2100 (Fig. 8.9.4). In lower concentration scenarios, fuel switching occurs sooner. Uncertainty matters in all the pathways considered (Bastani et al., 2012; Wang et al., 2012) as IAM results show a large range, especially after 2050 (Pietzcker et al., 2013). The long-term mix of fuels and technologies are difficult to foresee, especially within road transport, but liquid fuels should dominate the sector at least up to 2050. Model assumptions differ as to the alternative fuels that would replace them, reflecting the large uncertainties on technology cost, performance, as well as regulatory environment, consumer choice and fuel prices (Krey and Clarke, 2011). In terms of direct emission reductions, biofuels tend to have a more important role in a shorter term (up to 2050), after which wide-spread electrification and hydrogen use occurs.

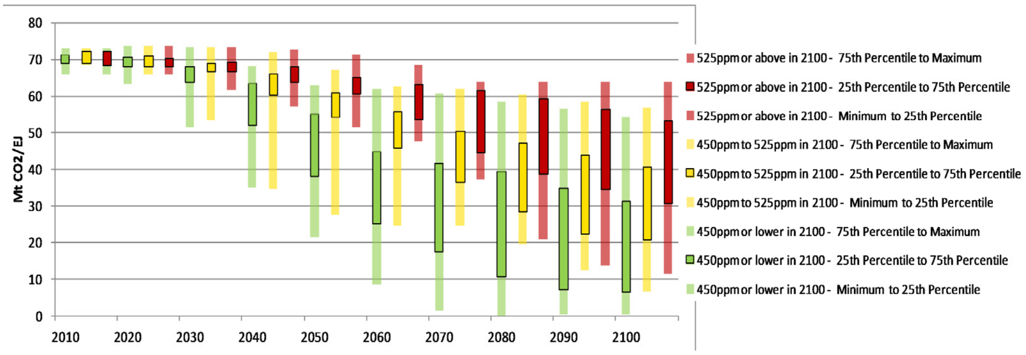

Figure 8.9.4 Global fuel carbon intensity in the transport sector out to 2100 based on integrated assessment models with various levels of CO_2 concentrations (Source: AR5 Scenario Database).

Decoupling transport demand from GDP appears to take place earlier for freight than for passengers. However, this may not be sufficient to reduce GHG emissions to levels that are compatible with more stringent stabilization goals. Furthermore, it has been accepted that compared with other energy consuming sectors, transport proves difficult to decarbonize before 2070 (Pietzcker et al., 2013). The strong increase in transport activity highlights the importance of rapid deployment of advanced fuel and vehicle mitigation technologies. IAM outputs indicate that technology substitution is less sensitive than fuels to changes in prices, but these models have limited ability to assess behavioral changes and their impact on modal shift, avoiding journeys, and modifying urban form.

8.9.2 Sectoral transformational pathways- implications from a bottom up perspective

There are differences between the outcomes of top-down (IAM) studies and bottom-up transport scenario analyses due to variations in assumptions, the degree of detail in input data, and treatment of alternatives. The set of conditions required for reaching climate mitigation targets, from either a bottom-up or top-down model perspective, is similar. It involves changes in fuel choices, vehicle technology, travel modes and infrastructure (Uherek et al., 2010).

The greater possibilities for assessing disaggregated level information in bottom-up studies result in further insights into areas and measures usually not represented in global climate-stabilization models. The greater level of detail in the bottom-up transport studies increases the likelihood of results showing a higher mitigation potential and variations in outcomes.

- Bottom-up scenarios find more emission reduction potential evident from a higher propensity for modal shifts, for example, from LDVs to bus rapid transit (BRT) and to non-motorised transport options (8.6.1, 8.4.2 and for freight 8.4.3). Sectoral analyses suggest that up to 20% of transport demand could be reduced by more compact cities, modal shift and behavioural change (8.3; 8.4) (IEA, 2009). For example, dynamic developments in BRT, which include dedicated lanes for buses and stops that enable level boarding, can deliver a full urban network, be implemented faster and at a cost affordable to many cities (UN-Habitat, 2009, 2011; Deng and Nelson, 2011). Bottom-up models highlight the potential contribution of policies aimed at achieving a change in consumer behavior that result in lowering passenger and freight transport demand by influencing preferences towards more sustainable travel options (GEA, 2012; IEA, 2012) These preferences are often difficult to assess (8.3.5) and are poorly addressed in IAMs.
- The mitigation potential of already viable technology options to reduc energy intensity (8.3, and Table 8.6.1) is often shown to be greater in bottom-up studies. For example, a decrease

in UK of about 20% of total distance travelled per capita by 2050 compared to 2007, and of total passenger transport fuel demand by 40% was projected (Anable et al., 2012). In China, fuel demand by all modes in 2050 is slightly below 2005 levels (Huo and Wang, 2012), and for LDVs only 40% of the 2010 demand (Harvey, 2012). In the US it has been estimated that the combination of travel demand management, biofuels, PEVs and FCVs could result in up to an 80% reduction in GHG emission levels below 1990 levels in 2050 (McCollum and Yang, 2009).

- Bottom-up scenarios often incorporate greater reservations about fuel intensity uncertainties, though this is also seen to some degree in many top-down scenarios. Options such as advanced biofuels, low-carbon electricity and hydrogen, will require time to make substantial contributions to climate change mitigation efforts (Salter et al., 2011).

The overall conclusion that emerges from both bottom-up and top-down studies is that achieving stabilisation goals will require major mitigation contributions to come from the transport sector and that the timing for a transition needs to be consolidate over the next few decades (IEA, 2008, 2012d; DOE/EIA, 2010; WEC, 2011; GEA, 2012).

8.9.2.1 Transformational possibilities

The transformation of the transport system will require a capacity for it to succeed from a systems perspective when designing policies for both demand and supply sides of the market. Policies will also be needed to support critical and structural/cultural changes ensuring that social objectives (8.7) are not subdued (McCollum and Yang, 2009; Kahn Ribeiro et al., 2012). From a system perspective, the integration of energy supply with energy demand, including electrification, can only be effectively achieved when low-carbon fuels are used for power generation and when a flexible interaction between the supply and demand sides of the system can interact (IEA, 2012d) .

From both the demand and supply sides, new technologies may take decades to reach large cumulative production volumes in order to reduce costs and achieve competitive positions leading to very slow transitions (Baptista et al., 2010; Eppstein et al., 2011). For example, it is likely to take the deployment of 5-10 million vehicles over 15-20 years for either BEVs or FCVs to compete with ICE vehicles (IEA, 2011a). On the other hand, the total costs of building new infrastructure may not be high compared to the overall costs of alternatives. For example, hydrogen fuel networks in the US have been estimated to cost tens to a few hundred billion dollars over a few decades, compared to around USD 1 trillion required for oil infrastructure developments in the same period (Ogden and Lorraine, 2011).

Structural changes and additional infrastructure is required to increase capacities to not only hold the modal share in an environment with increasing travel demand, but to increase the contribution of more efficient transport modes to the overall transport task (ITF, 2009). The lead time for transport infrastructure development is considerable (Short and Kopp, 2005), which makes swift changes in the capacity of public transport harder to achieve.

Some emerging countries have shown transformative processes in the development of public transport infrastructure. In just over one decade the city of Shanghai, for example, has built the world's biggest metro after the previous decade was dedicated to accommodating the car (ADB, 2012a). There are now 82 metro systems being built in Chinese cities and 14 in Indian cities (ADB, 2012a; Newman and Matan, 2013b). An integration of the transport system is expected to lead to a more efficient system and better service to users, particularly when combined with a willingness to allocate resources to provide better services (Givoni and Banister, 2010).

Mitigation transport policies will ultimately be aimed at changing travel behaviour directly, changing the attributes of purchased products, or changing the local physical environment and public transport technologies. Assessing the factors and feedbacks relating to consumer decision making is important (Stepp et al., 2009). Desired cultural changes involve a closer and systemic linkage between land use and transport decisions through institutional and policy reform; expanding usage of non-motorized modes; a willingness to embrace non-physical infrastructural solutions in transport (and land use) planning; courage to internalize or make explicit the environmental and social costs of transport to incentivize sustainable choices; a willingness to replace forecasting with backcasting paradigms in thinking and planning for development; a willingness to formally consider alternatives that subsidize the future with the goal of improving the social quality of life in the longer term; and an increasing commitment to use education (general public and institutional) as a tool to cultivate more sustainable lifestyles (Amekudzi et al., 2011; Kahn Ribeiro et al., 2012).

8.9.3 Sustainable development, and regional and national implications for developing countries

By 2100, most transport emissions could come from fast developing regions of the world. Urban areas, where 70% of the population will live in 2050, have a central role to play in global efforts for climate mitigation. One of the difficulties of long term assessments is how to interpret the evolution of rapidly growing developing countries like China (Huo et al., 2007; Huo and Wang, 2012) and whether the growth of transport energy use per capita will stabilize at a similar level of economic development than the US (70 TJ/capita / year) or Japan (25 TJ/capita / year). Direct CO_2 emissions from transport in developing countries could continue to grow steadily or follow OECD countries by peaking then declining. This depends on the stringency of mitigation policies relating to vehicle energy efficiency and fuel switching (Fig. 8.9.5).

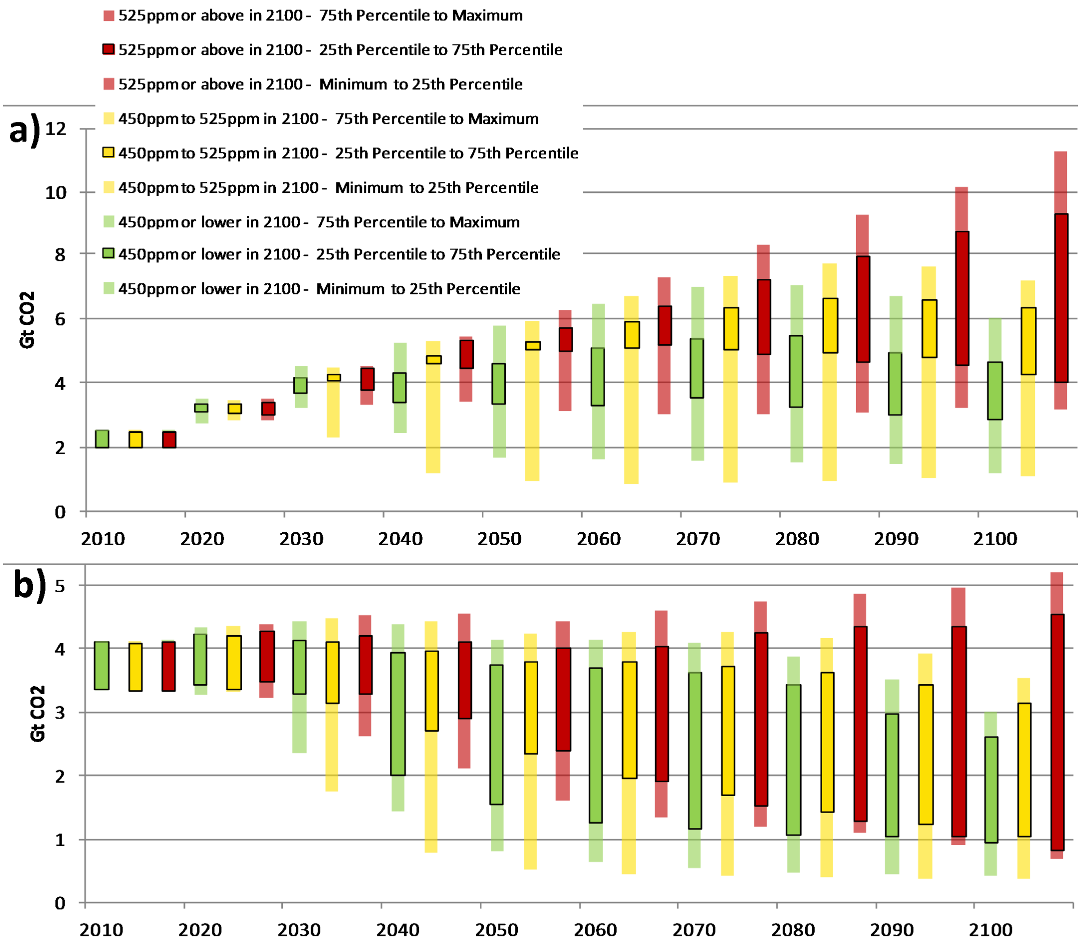

Figure 8.9.5. Regional direct CO_2 emissions from transport based on a comparison of several integrated assessment models that give different levels of CO_2 concentrations by 2100. **(a)** Asia, Middle East, Africa and Latin America **(b)** OECD90 and countries from the transition economies of Eastern Europe and the former Soviet Union. (Source: AR5 Scenario Database)

The likelihood that Chinese and Indian cities reach the current levels of transport GHG emissions equivalent to US cities is low as these nations are starting from a much lower level of per capita travel demand (Millard-Ball and Schipper, 2011; Kahn Ribeiro et al., 2012; Cuenot et al., 2012; Figueroa, Kobayashi, et al., 2013). In addition, they may evolve into land use and transport patterns that resemble other Asian nations that have managed to stabilize their GHG emissions per capita at a level half that of the US and even lower for transport-related GHG emissions (ADB, 2012a).

Furthermore, the rapid speed of both urbanisation and motorisation that many non-OECD countries are experiencing is proceeding under difficult realities: road and public transport systems are in dire conditions, countries face constraints of technical and financial resources, there is a dearth of infrastructure governance capacity, and the gap between the pace of growth of detrimental impacts of motorisation and effective action is widening (Kane, 2010; Li, 2011; Vasconcellos, 2011). These challenges are not always matched with the capacity-competences, funding, legal frameworks and rights to innovate that are needed to act effectively (Kamal-Chaoui and Plouin, 2012; Lefèvre, 2012). The significant role of initiatives for public funding reallocation to sustainable and climate-friendly transport funding have been recently demonstrated (Wittneben et al., 2009; Bongardt et al., 2011).

In rural areas, over a billion people worldwide have no adequate access to a transport system and only 13% of roads in low-income countries are paved compared to 92% in high income countries (Santos et al., 2010; World Bank, 2010; UN-Habitat, 2011). Improved accessibility can mean less time spent travelling by the urban poor and better access to basic education and health services. Improving road conditions and investments in rail, and public transport networks are key factors for developing countries to improve conditions for trade and economic growth (Frankel and Romer, 1999) but availability of adequate financial resources can be a barrier (8.8) (World Bank, 2010).

There are contrasts between the goals and policy recommendations for sustainable transport and climate mitigation applicable to non-OECD countries. Transport can be an agent of sustained urban development that prioritizes goals for equity and emphasizes accessibility, traffic safety and time savings for the poor with minimal detriment to the environment and human health (Vasconcellos, 2001; Tiwari, 2002; Amekudzi et al., 2011; Li, 2011; Kahn Ribeiro and Figueroa, 2013). Strategies need to be found that follow a clear political vision and agenda that supports poverty alleviation, enhances mobility opportunities and basic access, and services delivery to support economic growth (Kane, 2010; Li, 2011; Kahn Ribeiro et al., 2012).

The relationship between decarbonisation pathways for the transport sector and sustainable development more generally is diverse and includes the potential for a number of co-benefits, but also trade-offs (8.7) (Creutzig and He, 2009; Zusman et al., 2012; Creutzig et al., 2012b)(Kahn Ribeiro and Figueroa, 2013). Behavioural changes resulting in more environmentally sustainable lifestyles without compromising human quality of life and economic competitiveness in all countries are a critical transformational opportunity and arguably indispensable to global sustainable development in the long term (Roy et al., 2012). Under-resourced local governments, technical and financial resource scarcity, and the difficulties of representing a highly complex and changing context with limited data and information are barriers that create challenges for transport sustainability and climate mitigation in non-OECD countries (Vasconcellos, 2001, 2011; Dimitriou, 2006; Kane, 2010; Figueroa, Kobayashi, et al., 2013).

The success of public transport systems at climate change mitigation measures depends on the directions of the modal shift (Bongardt et al., 2011; La Branche, 2011). If bicycle and para-transit trips are shifted to LDV or light-rail travel, then GHG emissions may increase. Such alternatives should also be assessed in the context of the broader multiple objectives of sustainable development (including social cohesion and equity, quality of life, health). They can be incorporated with critical priorities and constraints in different socio-economic contexts (Amekudzi et al., 2009). The relative marginal socio-economic costs and benefits of various alternatives can be context sensitive with respect to sustainable development (Amekudzi, 2011). Developing the capacity (analytical and data) for multi-objective evaluation and priority setting is an important part of the process of cultivating sustainability and climate mitigation thinking and culture in the long term.

Box 8.1: Least Developed Countries (LDC)s: Transport, Climate Change and Sustainable Development

[TSU COMMENT TO REVIEWERS: Boxes highlighting further LDC-specific issues are included in other chapters of the report (see chapter sections 1.3.1, 2.1, 6.3.6.6, 7.9.1, 8.9.3, 9.3.2, 10.3.2, 11.7, 12.6.4, 16.8) and a similar box may be added to the Final Draft of chapters, where there is none in the current Second Order Draft. In addition to general comments regarding quality, reviewers are encouraged to comment on the complementary of individual boxes on LDC issues as well as on their comprehensiveness, if considered as a whole.]

Least Developed Countries (LDCs) are the least developed among developing countries. They are particularly vulnerable because they have the lowest gross national income (GNI) per capita, the lowest state of human development in terms of health and nutrition and education, and the lowest economic vulnerability index - an indicator of the risk posed to a country's development by exogenous shocks (UN, 2009). Populations in these countries may be as vulnerable to social and economic factors as they are to climate factors. Effective policies to address climate change through the transport sector in these countries will place heavy emphasis on **building economic and social resilience** as a risk management strategy (to reduce the vulnerabilities of these countries to climate change), while working to sidestep the historic environmental and social burdens of economic development, and progressively working to reduce and reverse their climate change footprints (or their share contributions to the changing climate). If preservation of human lives (and then enhancement of the quality of life is a secondary objective once this primary objective has been sufficiently achieved), then policies to address the changing climate in LDCs must necessarily be developed in the context of the countries' economic and social vulnerabilities. The interaction of all these factors – economic, social and environmental - thus calls **for integrated systems decision making** to prioritize and allocate resources for the development of transportation that improves access to basic services and amenities such as healthcare, food markets and schools, while leapfrogging the environmental burdens of development that have been associated with the transportation and related sectors, and reducing the carbon and GHG footprints of transportation.

Effective transportation planning will **prioritize safety**. It will involve developing initiatives to improve the safety of rural and urban travelers, beginning with lower-hanging fruit that can save the lives of non-motorized and motorized rural and urban system users. **Enforcement of laws, rules and regulations** will be critical to address safety and other risks within existing transportation systems. Superior transportation planning in this context will call for more **effective institutions** with the collaboration of transport and related authorities for land use planning and management, public health, agriculture, education, etc., for **integrated transportation planning**, i.e.,, transportation plans that provide better access to food, healthcare, education; as well as plans that promote trade more effectively. **Environmentally-conscious planning** in these contexts will seek application of technologies that can reduce environmental burdens of development – to a lesser scale than they have been experienced historically.

While LDCs must address both risks and opportunities for sustainable development in the context of the changing climate, and make efforts to mitigate their share of carbon and GHGs, their priorities arguably lie more with **building resilience** in their areas of highest risks as far as sustainable development and sustainability are concerned. While they may be interested in leapfrogging the environmental and social burdens of economic development, they may also be **intentional about the growth models and scenarios, and development lifestyles that they adopt**. For example, they may choose through their policymaking to intentionally develop organically and incrementally around their most critical areas of risk (and opportunity). For example, the slow cities movement, originated in Italy in 1999 and spreading across Europe, is demonstrating that cities that develop organically, seeking to sidestep economic and cultural homogenization and standardization, and to preserve the social, economic and cultural characteristics of different localities – can develop calmer, less polluted physical environments, conserving local crafts, produce, cuisine and other positive local attributes. Slow city values include the urban revitalization and historic preservation, alternative energy systems, promotion of organic culture, banning of genetically-modified foods and organisms, preservation of local tradition and heritage, signage and light regulations, building awareness of the local citizenry for slow city goals (Knox, 2005; Mayer and Knox, 2006). LDC cities may gradually build resilience through the development of increasingly robust social-economic-environmental systems, where there is a clear vision that is developed by local leaders and communities.

Effective comprehensive development efforts that elevate climate change considerations in LDCs will include efforts to develop or improve institutional effectiveness to support integrated planning (involving transportation, land use, energy, agriculture and public health authorities) that uses transportation as a driver for developing economic and social resilience. Such efforts will prioritize the application of technologies with a proven track or promise for reducing the historical environmental and social burdens of economic development; they will be intentional about determining and defining the types of cities and lifestyles that are desirable in the longer term and developing policies to implement them (including the necessary outreach and public education); they will distinguish between effective urban and rural policies, clarify shorter-term actions and longer-term initiatives and prioritize higher-impact and shorter-term actions while working to develop longer-term initiatives. Such efforts will also include serious steps to achieve effective law enforcement.

8.10 Sectoral policies

This section addresses policies and evaluation criteria for the transport sector. Categorization and evaluation of policies across all sectors are presented in Chapters 14 and 15. In this section, for each major transport mode, policies and strategies are categorized by policy type: as regulatory or market-based, or to a lesser extent as informational, voluntary, or government provided (such as public R&D investment, infrastructure, and transit services).

Aggressive policy intervention is needed to reduce fuel carbon intensity, energy intensity of modes, and activity levels (8.9). The mobility needs, complex choices and priority setting issues raised by the rapid growth of transport demand taking place in non-OECD countries highlight the importance of placing climate-related transport policies in the context of goals for sustainable urban development (Kahn Ribeiro S, et al., 2007; Bongardt et al., 2011) (8.9). The scale of urban growth and population redistribution from rural to urban areas in emerging and developing countries is expected to continue. This implies a huge increase in demand for urban infrastructure and motorized transport, especially in medium-size cities (Grubler et al., 2011).

In countries and regions with low levels of car ownership, opportunities exists for local and national governments to manage the rising vehicle demand (8.10.1) (Wright and Fulton, 2005; IEA, 2009a) in ways that support economic growth (Kane, 2010) and provide broad social benefits (Kato et al., 2005). Local history and social culture shape the specific problem together with equity implications and policy aspirations that ultimately determine what will become acceptable solutions (Vasconcellos, 2001; Dimitriou, 2006; Kane, 2010; Li, 2011; Verma et al., 2011).

Policies to support sustainable transport can simultaneously improve local transport services and enhance the quality of environment and urban living, almost always boosting both climate change mitigation and energy security (ECMT, 2004; WBCSD, 2004, 2007; World Bank, 2006; Banister, 2008a; IEA, 2009a; Bongardt et al., 2011; Ramani et al., 2011; Kahn Ribeiro et al., 2012). Diverse attempts have been made by transport agencies in OECD countries to define and measure policy performance (OECD, 2000; CST, 2002; Banister, 2008a; Ramani et al., 2011). The type of policies, their timing and chance of successful implementation are context dependent (Santos et al., 2010).

Generally speaking, market-based instruments, such as carbon taxes and carbon cap-and-trade, are highly effective at incentivizing all mitigation options simultaneously (Flachsland et al., 2011). However, transport fuel suppliers and end-users react weakly to price signals especially with passenger travel (Creutzig, McGlynn, et al., 2011; Yeh and McCollum, 2011). Market policies are economically more efficient at reducing emissions than setting fuel carbon intensity standards (Holland et al., 2009; Sperling and Yeh, 2010; Chen and Khanna, 2012; Holland, 2012). However, financial instruments such as carbon taxes must be relatively large to achieve reductions similar to those possible with regulatory instruments. As a result, to gain large emissions reductions a suite of policy instruments will be needed (NRC, 2011c; Sperling and Nichols, 2012), including voluntary schemes which have been successful in some circumstances such as for the Japanese airline industry (Yamaguchi, 2010).

8.10.1 Road transport

A wide array of policies and strategies has been employed in different circumstances to restrain vehicle usage, manage traffic congestion and reduce energy use, air pollution and GHG emissions. These policies and strategies overlap considerably, often synergistically.

Historical trends of more and larger LDVs and longer distances travelled each year (Kahn Ribeiro S, et al., 2007) continue to occur in emerging economies and some developing countries, but they appear to be declining in OECD countries (8.9.2). The reason for the peaking of car use is not yet well understood, but policy seems to be playing little or no role. In contrast, policy can play a central role in reducing fuel consumption and GHG emissions from new road vehicles (Mayor and Tol, 2008).

Fuel carbon intensity. Flexible standards that combine regulatory and market features include the Californian low-carbon fuel standard (LCFS) (Sperling and Nichols, 2012) and the EU fuel quality directive (FQD). Fuel carbon intensity reduction targets for 2020 (10% for California and 6% for EU) are expected to be met by increasing the use of low-carbon biofuels, hydrogen and electricity. They are the first major policies in the world premised on the measurement of life-cycle GHG intensities (Yeh and Sperling, 2010; Creutzig, McGlynn, et al., 2011) although interpretation of life-cycle analyses can be misleading since upstream emissions (Lutsey and Sperling, 2012) and emissions associated with infrastructure and vehicle manufacturing (Kendall and Price, 2012) should also be included (8.3.4 and Annex II).

Biofuel policies have become increasingly controversial as more scrutiny is applied to the environmental and social equity impacts (Chapter 11, Annex). The EU adopted aggressive biofuel policies in 2007 and the US greatly strengthened biofuel sales regulations about the same time (Yeh and Sperling, 2013). The US mandated 61 billion litres of cellulosic biofuels by 2022, but less than one million was produced in 2012. The effectiveness of these policies is uncertain, but promising in that they provide a durable policy framework, harness market forces (allowing trading of credits), and provide flexibility to industry in determining how best to reduce fuel carbon intensity. Other related biofuel policies include various subsidies (IEA, 2011d) and mandatory targets (REN21, 2012). The US discontinued its longstanding national tax subsidy for ethanol in 2011.

Because economy-wide market instruments are not the predominant policy tool being used to reduce GHG intensity, a suite of regulatory and other complementary policy instruments are needed. The current approach is to design separate instruments for vehicles and fuels. The challenge is to make them consistent and coherent. For instance, the energy efficiency and GHG standards for vehicles in Europe and the US give multiple credits to PEVs and FCVs, and assign them zero upstream emissions, which is technically incorrect but designed to be an implicit subsidy (Lutsey and Sperling, 2012).

Regulatory instruments that ban high-polluting vehicles from city centres result in greater walking, biking, and mass transit use, but also result in switching from petroleum fuels such as to electric bikes as in China and to natural gas for three-wheelers and buses as in India (Salter and Newman, 2011). A more explicit regulatory instrument is a zero emission vehicle mandate, as adopted by California in 1990 to improve local air quality, and now also adopted by 10 other US states to cover almost 30% of the US market. This policy is now also premised on reducing GHGs. It requires about 15% of new vehicles in 2025 to be a mix of PEVs and FCVs (CARB, 2012).

Energy intensity. The element of transport that shows the greatest promise of being on a trajectory to achieve large reductions in GHG emissions by 2050 is reducing energy intensity in LDVs. Policies are being put in place to achieve dramatic improvements in vehicle efficiency, stimulating automotive companies to make major investments. Several countries have adopted aggressive targets (Fig. 8.10.1) including the US where standards aim to cut new vehicle energy use and GHG emissions per kilometre by 50% between 2010 and 2025. Some emerging economies, including China, are also adopting increasingly aggressive performance standards (Wang et al., 2010).

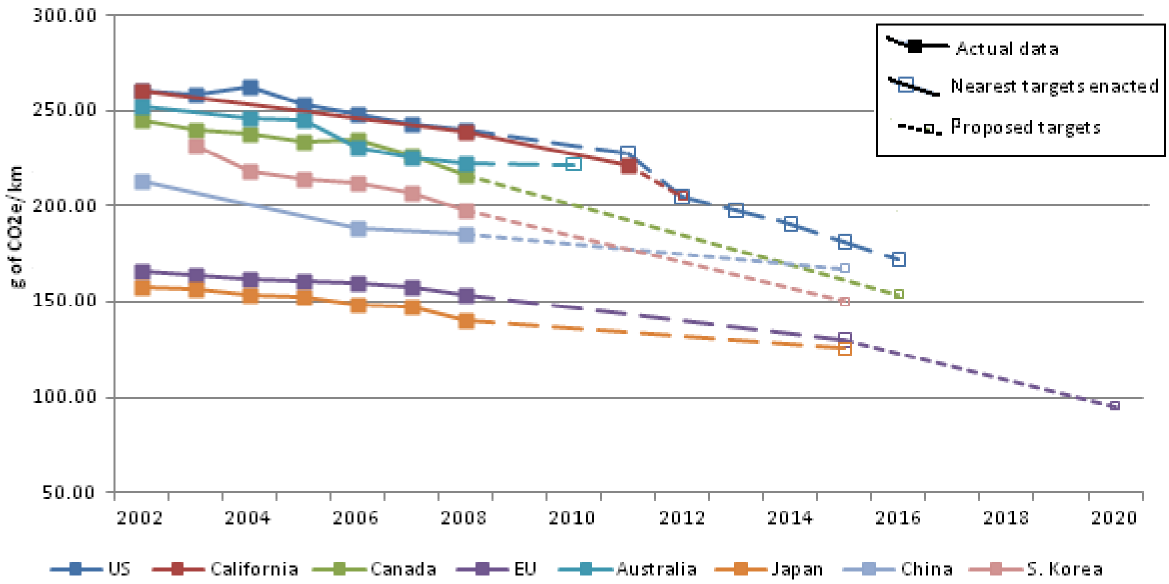

Figure 8.10.1. LDV GHG emissions targets in selected countries and European Union, adjusted to provide a comparison using the same test driving cycle. Sources: (An et al., 2007; Creutzig, McGlynn, et al., 2011) [Authors' note to reviewers: Will be updated to incorporate new standards, e.g. U.S. 2016-2025 standards.]

Regulatory standards focused on fuel consumption and GHG emissions vary in their design and stringency. Some strongly stimulate reductions in vehicle size (as in Europe) and others reduce vehicle weight (as in the US) (CCC, 2011). All have different reduction targets. As of April 2010, 17 European countries had implemented taxes on LDVs wholly or partially related to CO_2 emissions. Regulatory standards require strong market instruments such as fuel and vehicle circulation and purchase taxes to limit rebound effects and align market signals with regulations as they become tighter over time. Several European countries have established revenue-neutral feebate schemes (a combination of *rebates* awarded to purchasers of low carbon emission vehicles and *fees* charged to purchasers of less efficient vehicles) (Greene and Plotkin, 2011). Annual registration fees can have similar effects if linked directly with carbon emissions or with related vehicle attributes such as engine displacement, engine power or vehicle weight (CARB, 2012). One concern with market-based policies is their differential impact across population groups such as farmers needing robust vehicles to combat rugged terrain and poor quality roads. Equity adjustments can be made so that farmers and large families are not penalized for having to buy a large car or van (Greene and Plotkin, 2011).

LDV standards in place in the US could cut in half fuel consumption per vehicle km between 2010 and 2025 (EPA, 2011). The estimated cost of USD 1900 per vehicle for increasing the fuel economy from 8.3 l/100 km in 2016 to 5.9 l/100km in 2025 is significantly less than the fuel savings that would accrue to each vehicle even with the low fuel prices in the US. Simulation and cost assessment modelling, based on extensive inputs from industry, indicated that major changes in vehicle technology would be elicited, but that the standards would not by themselves motivate significant shifts away from petroleum-fuelled ICEs with PEV shaving only 1% market share if automakers were to meet the 2025 standards based only on economics.

The potential improvements in efficiencies of HDVs at around 50% (NRC, 2010b) are unlikely to be realized in the near to medium term. Truck manufacturers tend to be smaller than car manufacturers and have less R&D capability. HDV use is more varied than for LDVs and engines are matched with very different designs and loads. For these reasons, HDV efficiency policies have lagged behind those for LDVs. However, China implemented fuel consumption limits in July 2012 (MIIT, 2011); Japan set modest fuel efficiency standards in 2005 to be met by 2015 (Atabani et al., 2011); California required compulsory retrofits to reduce aerodynamic drag and rolling resistance (Atabani et al., 2011); the US adopted standards for new trucks and buses manufactured from 2014 through 2018 (Greene and Plotkin, 2011); and the EU intends to pursue similar actions including performance standards and fuel efficiency labelling by 2014 (Kojima and Ryan, 2010). Aggressive air pollution standards since the 1990s for NOx and particulate matter emissions from HDVs in many OECD countries have resulted in a fuel consumption penalty of 7% to 10% (IEA, 2009; (Tourlonias and Koltsakis, 2011). However, GHG reduction effects are less since particulate matter pollution standards can have significant climate benefits as short-lived, black carbon emissions strongly impact on climate change (8.2).

Activity reduction. A vast and diverse mix of policies is used to restrain and reduce the use of LDVs, primarily by focusing on land use patterns, public transport options, and pricing. Other policy strategies to reduce activity include improving traffic management (Barth and Boriboonsomsin, 2008); better truck routing systems (Suzuki, 2011); and smart real-time information to reduce time searching for a parking space. Greater support for innovative services using information and communication technologies, such as dynamic ride-sharing and demand-responsive para-transit services (8.4), creates still further opportunities to shift toward more energy efficient modes of travel.

Policies can be effective at reducing dependence on automobiles, as shown by comparing Shanghai with Beijing that has three times as many LDVs even though they have similar levels of affluence, the same culture, and are of a similar size (Hao et al., 2011). Shanghai limited the ownership of LDVs by establishing an expensive license auction, built fewer new roads, and invested more in public transport whereas Beijing built an extensive network of high capacity expressways and did little to restrain car ownership or use until recently. Since 2008, it has curtailed vehicle use by forbidding cars to be used one day per week and then by sharply limiting the number of new license plates issued each year (Santos et al., 2010; Hao et al., 2011). The main aims to reduce air pollution, traffic congestion and costs of road infrastructure exemplify how policies to reduce vehicle use are generally, but not always, premised on non-GHG co-benefits. European cities have long pursued demand reduction strategies, with extensive public transport supply, strict growth controls, and more recent innovations such as bicycle sharing. California created more liveable communities by reducing vehicle use, land use sprawl, and GHG emissions from passenger travel. The California law calls for 6-8% reduction in GHG emissions from passenger travel per capita (excluding changes in fuel carbon intensity and vehicle energy intensity) in major cities by 2020, and 13-16% per capita by 2035 (Sperling and Nichols, 2012).

The overall effectiveness of initiatives to reduce or restrain road vehicle use varies dramatically depending on local commitment and local circumstances, and the ability to adopt synergistic policies and practices by combining pricing, land use management, and public transport measures. A broad mix of policies successfully used to reduce vehicle use in OECD countries, and to restrain growth in emerging economies, includes pricing to internalize energy, environmental, and health costs; strengthening land use management; and providing more and better public transport. Policies to reduce LDV activity can be national, but mostly they are local, with the details varying from one city to another.

Some policies are intrinsically more effective than others. For instance, fuel taxes will reduce travel demand but drivers are known to be relatively inelastic in their response (Hughes et al., 2006; Small and van Dender, 2007), though drivers are more elastic when price increases are planned and certain (Sterner, 2007). Pricing instruments such as congestion charges, vehicle registration fees, road tolls and parking management can reduce LDV travel by inducing trip chaining, modal shifts, and reduced use of cars (Litman, 2006). Policies and practices of cities in developing countries can be influenced by lending practices of development banks, such as the 2012 commitment to spend $175 billion on more sustainable transport projects, with a focus on Asia.

System efficiency

System efficiency improvements have been far greater in freight transport and aviation than surface passenger transport. Freight transport has seen considerable innovation in containerization and intermodal connections, as has aviation, though the effects on GHG emissions are uncertain. In surface passenger travel, efforts to improve system efficiency and inter-modality are hindered by conflicting and overlapping jurisdictions of many public and private sector entities and tensions between fiscal, safety, and equity goals. One outcome in most cities of developed countries through the second half of the 20th century was far greater investment in roads than in public transport (Owens, 1995; Goodwin, 1999). The 21st century, though, has seen increasing government investment in bus rapid transit and rail transit in OECD countries (Yan and Crookes, 2010; Tennøy, 2010), along with increasing support for bicycle use.

Since the 1960s, many cities have instigated supportive policies and infrastructure that have resulted in a stable growth in cycling (Servaas, 2000; Hook, 2003; TFL, 2007; NYC, 2012). In London, UK, the 2% cycle share of travel modes is targeted to increase to 5% in 2026 as a result of a range of new policies (TFL, 2010). However, in less developed cities such as Surabaya, Indonesia, 10% of total trips between 1 - 3 km are already by cycling (including rickshaws) in spite of unsupportive infrastructure and policies (Hook, 2003). Where cycle lanes have been improved, as in Delhi, greater uptake of cycling is evident (Tiwari and Jain, 2012b).

8.10.2 Rail transport

Rail transport serves 28 billion passengers globally (2495 billion p-km annually compared with aviation moving 2.1 billion passengers at 3940 billion p-km), and also carries 11.4 billion tonne of freight (8845 billion t-km) (Johansson et al., 2012). Specific energy and carbon intensities of rail transport are relatively small compared to some other modes (8.3). Policies to further improve system efficiency may improve competitiveness and opportunities for modal shift (Johansson et al., 2012). Train driver education and training policies can also assist (Camagni et al., 2002b).

Energy intensity. Driven largely by corporate strategies, the energy intensity of rail transport has been reduced by more than 60% between 1980 and 2001 in the US (Sagevik, 2006). Overall reduction opportunities of 45-50% are possible for passenger transport in the EU and 40-50% for freight (Andersson et al., 2011). Recent national policies in UK, Baltic and Germany appear to have resulted in 73% rail freight growth over the period 1995-2007in competition with road freight.

Fuel intensity. Roughly one third of rail transport is driven by diesel, two-thirds by electricity (Johansson et al., 2012). Policies to reduce fuel carbon intensity are therefore linked to a large extent to those for electricity production (Chapter 7; DLR, 2012). Both Sweden and Switzerland are running their rail systems at very low carbon emissions (Gössling, 2011).

System efficiency. China, Europe, Japan, Australia, Russia, US and several Middle-eastern and Northern African countries continue (or are planning) to invest in high-speed rail **(CRC, 2008; "China aims to ride high-speed trains into the future," 2011; UIC, 2012)**. It is envisaged that the worldwide track length of about 15000 km in 2012 will nearly triple by 2025 **(UIC, 2012)** due to government supporting policies **(Camagni et al., 2002b)** and compete with medium haul aviation.

8.10.3 Waterborne transport

The International Maritime Organization (IMO) has adopted mandatory measures to reduce GHG emissions from international shipping, the first mandatory GHG reduction regime for an international industry sector (IMO, 2011). There are few, if any, policies supporting the use of biofuels, natural gas or hydrogen for waterborne craft on inland waterways are unusual.

Energy intensity. IMO's energy efficiency design index (EEDI) sets technical standards for improving the energy efficiency of certain categories of new ships which, in turn, targets a 10% GHG emission reduction target from shipping (IMO, 2011). The EEDI may not meet the target if shipping demand increases faster than fuel carbon and energy intensities improve. The voluntary Ship Energy Efficiency Management Plan (SEEMP) becomes mandatory from 2015 (IMO, 2011) when a minimum energy efficiency level for different ship types and sizes is expected to cover as much as 70% of emissions from new ships and achieve approximately 25-30% reductions by 2030 compared with business-as-usual (IISD, 2011). It is estimated that in combination, EEDI requirements and SEEMP will cut CO_2 emissions from shipping by 13% by 2020 and 23% by 2030 (Lloyds Register and DNV, 2011).

8.10.4 Aviation

After the Kyoto Protocol assigned the responsibility for international aviation GHG emission reductions to the International Civil Aviation Organisation (ICAO) (Petersen, 2008), member states are working together with the industry towards voluntarily improving technologies, increasing the efficient use of airport infrastructure and aircraft, and adopting appropriate economic measures (ICAO, 2007b, 2010a). In 2010, the 190 states subscribing to ICAO agreed on a non-binding, global aviation strategy to reduce carbon emissions by 50% from 2005 to 2050; to improve fuel efficiency by an average of 2% per annum until 2050; achieve carbon neutral growth from 2020; and establish a medium-term global goal from 2020 (ICAO, 2010b). These aspirational goals exceed the assumptions made in many scenarios (e.g. (Mayor and Tol, 2010)).

Policy options in place or under consideration include regulatory instruments (fuel efficiency and emission standards at aircraft or system levels); market-based approaches (emission trading under caps, fuel taxes, emission taxes, subsidies for fuel efficient technologies); and voluntary measures including emission offsets (Daley & Preston, 2009). Environmental capacity constraints on airports also exist and may change both overall volumes of air transport and modal choice (Upham et al., 2004; Evans, 2010). National policies affect mainly domestic aviation, which covers about 30-35% of total air transport (IATA, 2009b; Wood et al., 2010; Lee et al., 2009).

The only current binding policy to mitigate emissions is the inclusion of air transport in the EU emission trading scheme (ETS) (Anger, 2010; Petersen, 2008), The EU is currently responsible for 35% of global aviation emissions (Preston et al., 2012) and the emission reduction target is 20% below 1990 levels by 2020, rising to 80-95% below these levels by 2050 (European Climate Foundation, 2011). The applicability of ETS policy for non-EU airlines (Malina et al., 2012) has been delayed for one year from November 2012 in anticipation of new ICAO initiatives towards a global market-based mechanism for all aviation emissions (ICAO, 2012).

Fuel carbon intensity. Policies do not yet exist to introduce low-carbon biofuels. However, the projected GHG emission reductions from the possible future use of biofuels as assumed by the aviation industry, vary between 19% of its adopted total emission reduction goal (Sustainable Aviation, 2008) to over 50% (IATA, 2009a) depending on the assumptions made for the other reduction options that include energy efficiency, improved operation and trading emission permits.

Energy intensity. The energy efficiency of jet-powered aircraft improved historically without any policies in force (Penner et al., 1999). The rate of fuel consumption reduction has slowed over time from an initial 3-6% in the 1950s to between 1 and 2% per year at the beginning of the 21st century (Bows et al., 2006; Fulton and Eads, 2004; Peeters et al., 2009; Peeters and Middel, 2007; Pulles et al., 2002) possibly due to increasing lead-times required to develop, certify and introduce new technology (Kivits et al., 2010).

System efficiency. The interconnectedness of aviation services can be a complicating factor in adopting policies, but also lends itself to global agreements. Regional and national air traffic controllers can influence operational efficiencies. The use of market policies to reduce GHG emissions is compelling because it introduces a price signal that influences mitigation actions across the entire system. But like other aspects of the passenger transport system, a large price signal is needed with aviation fuels to gain significant reductions in energy use and emissions (Tol, 2007, Dubois et al., 2008; Peeters and Dubois, 2010a, OECD & UNEP, 2011)). Complementary policies to induce system efficiencies include policies to reduce tourism travel and divert it to more efficient modes (though aviation now has similar energy efficiencies per passenger km to cars and thus shorter trips are generally more important than switching to alternative modes). (Peeters & Dubois, 2010b). No country has adopted a low-carbon tourism strategy.

8.10.5 Infrastructure and urban planning

A modal shift from LDVs to other surface transport modes could be partly incentivised by policy measures that impose physical restrictions as well as pricing regimes. Car parking management is a simple form of cost effective strategy (Barter et al., 2003; Litman, 2006). Dedicated bus lanes, possibly in combination with a vehicle access charge for LDVs, can be a major instrument to achieving rapid shifts to public transport (Creutzig and He, 2009).

Policies that support the integration of moderate to high density urban property development with transit-oriented development strategies that mix residential, employment and shopping facilities, can encourage pedestrians and cyclists, thereby giving the dual benefits of reducing car dependence and preventing urban sprawl (Newman and Kenworthy, 1996; Cervero, 2004; Olaru et al., 2011). GHG savings (Trubka et al., 2010a; b; c) and co-benefits of health, productivity and social opportunity (Newman et al., 2009; Ewing and Cervero, 2010; Höjer, Dreborg, et al., 2011) could result if LDV trips could be reduced using polycentric city and comprehensive smart-growth policies (Dierkers et al., 2008). Policies to support the building of more roads, airports and other infrastructure can help relieve congestion in the short term but also induce travel demand (Duranton and Turner, 2011).

8.11 Gaps in knowledge and data

Assessing the mitigation potential of the transport sector is challenging due to gaps in the knowledge. Prices of crude oil products fluctuate widely as do those for alternative transport fuels. Future technological developments and costs of batteries*, fuel cells,* advanced biofuels *and vehicle designs* are uncertain. Assessments of the global potential and costs to mitigate transport GHG emissions are inconsistent leading to confusion. There are also important gaps in basic statistics and information on transport energy consumption especially in developing countries. There is little understanding of how and when people will choose to buy and use new types of low-carbon vehicles or use new types of mobility services (such as demand responsive transit or car sharing). A better knowledge of consumer travel behaviour is needed, particularly for aviation.

There is a poor understanding of how travelers will respond to combinations of strategies (mixes of land use, transit, vehicle options), which is especially important for fast-growing, developing countries where alternative modes to the car-centric development path could be deployed. For moving freight, data and understanding relating to logistical systems and their economic implications are poor. Hence it is difficult to design new low-carbon freight policies.

Understanding how low-carbon transport and energy technologies will evolve (via experience curves and innovation processes) is not well developed. In addition, the rate of social acceptance of new concepts such as LDV road convoys and driverless cars (both currently being demonstrated) is difficult to predict as is the level of related infrastructure investments needed. Recent rapid developments in metro systems in several cities, such as Shanghai, illustrate how quickly new transport systems can occur when the demand, policies and investments are put in place.

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