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Transport and its infrastructure

Coordinating Lead Authors:

Suzana Kahn Ribeiro (Brazil), Shigeki Kobayashi (Japan)

Lead Authors:

Michel Beuthe (Belgium), Jorge Gasca (Mexico), David Greene (USA), David S. Lee (UK), Yasunori Muromachi (Japan), Peter J. Newton (UK), Steven Plotkin (USA), Daniel Sperling (USA), Ron Wit (The Netherlands), Peter J. Zhou (Zimbabwe)

Contributing Authors:

Hiroshi Hata (Japan), Ralph Sims (New Zealand), Kjell Olav Skjolsvik (Norway)

Review Editors:

Ranjan Bose (India), Haroon Kheshgi (USA)

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EXECUTIVE SUMMARY

Transport activity, a key component of economic development and human welfare, is increasing around the world as economies grow. For most policymakers, the most pressing problems associated with this increasing transport activity are traffic fatalities and injuries, congestion, air pollution and petroleum dependence. These problems are especially acute in the most rapidly growing economies of the developing world. Mitigating greenhouse gas (GHG) emissions can take its place among these other transport priorities by emphasizing synergies and co-benefits *(high agreement, much evidence)*.

Transport predominantly relies on a single fossil resource, petroleum that supplies 95% of the total energy used by world transport. In 2004, transport was responsible for 23% of world energy-related GHG emissions with about three quarters coming from road vehicles. Over the past decade, transport's GHG emissions have increased at a faster rate than any other energy using sector *(high agreement, much evidence)*.

Transport activity will continue to increase in the future as economic growth fuels transport demand and the availability of transport drives development, by facilitating specialization and trade. The majority of the world's population still does not have access to personal vehicles and many do not have access to any form of motorized transport. However, this situation is rapidly changing.

Freight transport has been growing even more rapidly than passenger transport and is expected to continue to do so in the future. Urban freight movements are predominantly by truck, while international freight is dominated by ocean shipping. The modal distribution of intercity freight varies greatly across regions. For example, in the United States, all modes participate substantially, while in Europe, trucking has a higher market share (in tkm[1]), compared to rail *(high agreement, much evidence)*.

Transport activity is expected to grow robustly over the next several decades. Unless there is a major shift away from current patterns of energy use, world transport energy use is projected to increase at the rate of about 2% per year, with the highest rates of growth in the emerging economies, and total transport energy use and carbon emissions is projected to be about 80% higher than current levels by 2030 *(medium agreement, medium evidence)*.

There is an ongoing debate about whether the world is nearing a peak in conventional oil production that will require a significant and rapid transition to alternative energy resources. There is no shortage of alternative energy sources, including oil sands, shale oil, coal-to-liquids, biofuels, electricity and

hydrogen. Among these alternatives, unconventional fossil carbon resources would produce less expensive fuels most compatible with the existing transport infrastructure, but lead to increased carbon emissions *(medium agreement, medium evidence)*.

In 2004, the transport sector produced 6.3 $GtCO_2$ emissions (23% of world energy-related CO_2 emissions) and its growth rate is highest among the end-user sectors. Road transport currently accounts for 74% of total transport CO_2 emissions. The share of non-OECD countries is 36% now and will increase rapidly to 46% by 2030 if current trends continue *(high agreement, much evidence)*. The transport sector also contributes small amounts of CH_4 and N_2O emissions from fuel combustion and F-gases (fluorinated gases) from vehicle air conditioning. CH_4 emissions are between 0.1–0.3% of total transport GHG emissions, N_2O between 2.0 and 2.8% (based on US, Japan and EU data only). Worldwide emissions of F-gases (CFC-12+HFC-134a+HCFC-22) in 2003 were 0.3–0.6 $GtCO_2$-eq, about 5–10% of total transport CO_2 emissions *(medium agreement, limited evidence)*.

When assessing mitigation options it is important to consider their lifecycle GHG impacts. This is especially true for choices among alternative fuels but also applies to a lesser degree to the manufacturing processes and materials composition of advanced technologies. Electricity and hydrogen can offer the opportunity to 'de-carbonise' the transport energy system although the actual full cycle carbon reduction depends upon the way electricity and hydrogen are produced. Assessment of mitigation potential in the transport sector through the year 2030 is uncertain because the potential depends on:
- World oil supply and its impact on fuel prices and the economic viability of alternative transport fuels;
- R&D outcomes in several areas, especially biomass fuel production technology and its sustainability in massive scale, as well as battery longevity, cost and specific energy.

Another problem for a credible assessment is the limited number and scope of available studies of mitigation potential and cost.

Improving energy efficiency offers an excellent opportunity for transport GHG mitigation through 2030. Carbon emissions from 'new' light-duty road vehicles could be reduced by up to 50% by 2030 compared to currently produced models, assuming continued technological advances and strong policies to ensure that technologies are applied to increasing fuel economy rather than spent on increased horsepower and vehicle mass. Material substitution and advanced design could reduce the weight of light-duty vehicles by 20–30%. Since the TAR (Third Assessment Report), energy efficiency of road vehicles has improved by the market success of cleaner direct-injection turbocharged (TDI) diesels and the continued market penetration of numerous incremental efficiency technologies.

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1   ton-km, "ton" refers to metric ton, unless otherwise stated.

Hybrid vehicles have also played a role, though their market penetration is currently small. Reductions in drag coefficients of 20–50% seem achievable for heavy intercity trucks, with consequent reductions in fuel use of 10–20%. Hybrid technology is applicable to trucks and buses that operate in urban environments, and the diesel engine's efficiency may be improved by 10% or more. Prospects for mitigation are strongly dependent on the advancement of transport technologies.

There are also important opportunities to increase the operating efficiencies of transport vehicles. Road vehicle efficiency might be improved by 5–20% through strategies such as eco-driving styles, increased load factors, improved maintenance, in-vehicle technological aids, more efficient replacement tyres, reduced idling and better traffic management and route choice *(medium agreement, medium evidence)*.

The total mitigation potential in 2030 of the energy efficiency options applied to light duty vehicles would be around 0.7–0.8 $GtCO_2$-eq in 2030 at costs <100 US$/$tCO_2$. Data is not sufficient to provide a similar estimate for heavy-duty vehicles. The use of current and advanced biofuels would give an additional reduction potential of another 600–1500 $MtCO_2$-eq in 2030 at costs <25 US$/$tCO_2$ *(low agreement, limited evidence)*.

Although rail transport is one of the most energy efficient modes today, substantial opportunities for further efficiency improvements remain. Reduced aerodynamic drag, lower train weight, regenerative breaking and higher efficiency propulsion systems can make significant reductions in rail energy use. Shipping, also one of the least energy intensive modes, still has some potential for increased energy efficiency. Studies assessing both technical and operational approaches have concluded that energy efficiency opportunities of a few percent to up to 40% are possible *(medium agreement, medium evidence)*.

Passenger jet aircraft produced today are 70% more fuel efficient than the equivalent aircraft produced 40 years ago and continued improvement is expected. A 20% improvement over 1997 aircraft efficiency is likely by 2015 and possibly 40 to 50% improvement is anticipated by 2050. Still greater efficiency gains will depend on the potential of novel designs such as the blended wing body, or propulsion systems such as the unducted turbofan. For 2030 the estimated mitigation potential is 150 $MtCO_2$ at carbon prices less than 50 US$/$tCO_2$ and 280 $MtCO_2$ at carbon prices less than 100 US$/$tCO_2$ *(medium agreement, medium evidence)*. However, without policy intervention, projected annual improvements in aircraft fuel efficiency of the order of 1–2%, will be surpassed by annual traffic growth of around 5% each year, leading to an annual increase of CO_2 emissions of 3–4% per year *(high agreement, much evidence)*.

Biofuels have the potential to replace a substantial part but not all petroleum use by transport. A recent IEA analysis estimates that biofuels' share of transport fuel could increase to about 10% in 2030. The economic potential in 2030 from biofuel application is estimated at 600–1500 $MtCO_2$-eq/yr at a cost of <25 US$/$tCO_2$-eq. The introduction of flexfuel vehicles able to use any mixture of gasoline[2] and ethanol rejuvenated the market for ethanol as a motor fuel in Brazil by protecting motorists from wide swings in the price of either fuel. The global potential for biofuels will depend on the success of technologies to utilise cellulose biomass *(medium agreement, medium evidence)*.

Providing public transports systems and their related infrastructure and promoting non-motorised transport can contribute to GHG mitigation. However, local conditions determine how much transport can be shifted to less energy intensive modes. Occupancy rates and primary energy sources of the transport mode further determine the mitigation impact. The energy requirements for urban transport are strongly influenced by the density and spatial structure of the built environment, as well as by location, extent and nature of transport infrastructure. If the share of buses in passenger transport in typical Latin American cities would increase by 5–10%, then CO_2 emissions could go down by 4–9% at costs of the order of 60–70 US$/$tCO_2$ *(low agreement, limited evidence)*.

The few worldwide assessments of transport's GHG mitigation potential completed since the TAR indicate that significant reductions in the expected 80% increase in transport GHG emission by 2030 will require both major advances in technology and implementation via strong, comprehensive policies *(medium agreement, limited evidence)*.

The mitigation potential by 2030 for the transport sector is estimated to be about 1600–2550 $MtCO_2$ for a carbon price less than 100 US$/$tCO_2$. This is only a partial assessment, based on biofuel use throughout the transport sector and efficiency improvements in light-duty vehicles and aircraft and does not cover the potential for heavy-duty vehicles, rail transport, shipping, and modal split change and public transport promotion and is therefore an underestimation. Much of this potential appears to be located in OECD North America and Europe. This potential is measured as the further reduction in CO_2 emissions from a Reference scenario, which already assumes a substantial use of biofuels and significant improvements in fuel efficiency based on a continuation of current trends. This estimate of mitigation costs and potentials is highly uncertain. There remains a critical need for comprehensive and consistent assessments of the worldwide potential to mitigate transport's GHG emissions *(low agreement, limited evidence)*.

While transport demand certainly responds to price signals, the demand for vehicles, vehicle travel and fuel use are significantly price inelastic. As a result, large increases in prices or taxes are required to make major changes in GHG emissions.

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2   US term for petrol.

Many countries do heavily tax motor fuels and have lower rates of fuel consumption and vehicle use than countries with low fuel taxes *(high agreement, much evidence)*.

Fuel economy regulations have been effective in slowing the growth of GHG emissions, but so far growth of transport activity has overwhelmed their impact. They have been adopted by most developed economies as well as key developing economies, though in widely varying form, from uniform, mandatory corporate average standards, to graduated standards by vehicle weight class or size, to voluntary industry-wide standards. The overall effectiveness of standards can be significantly enhanced if combined with fiscal incentives and consumer information *(medium agreement, medium evidence)*.

A wide array of transport demand management (TDM) strategies have been employed in different circumstances around the world, primarily to manage traffic congestion and reduce air pollution. TDMs can be effective in reducing private vehicle travel if rigorously implemented and supported (*high agreement, low evidence*).

In order to reduce emissions from air and marine transport resulting from the combustion of bunker fuels, new policy frameworks need to be developed. However ICAO endorsed the concept of an open, international emission trading system for the air transport sector, implemented through a voluntary scheme, or incorporation of international aviation into existing emission trading systems. Environmentally differentiated port dues are being used in a few places. Other policies to affect shipping emissions would be the inclusion of international shipping in international emissions trading schemes, fuel taxes and regulatory instruments *(high agreement, much evidence)*.

Since currently available mitigation options will probably not be enough to prevent growth in transport's emissions, technology research and development is essential in order to create the potential for future, significant reductions in transport GHG emissions. This holds, amongst others, for hydrogen fuel cell, advanced biofuel conversion and improved batteries for electric and hybrid vehicles *(high agreement, medium evidence)*.

The best choice of policy options will vary across regions. Not only levels of economic development, but the nature of economic activity, geography, population density and culture all influence the effectiveness and desirability of policies affecting modal choices, infrastructure investments and transport demand management measures *(high agreement, much evidence)*.

5.1   Introduction

Mobility is an essential human need. Human survival and societal interaction depend on the ability to move people and goods. Efficient mobility systems are essential facilitators of economic development. Cities could not exist and global trade could not occur without systems to transport people and goods cheaply and efficiently (WBCSD, 2002).

Since motorized transport relies on oil for virtually all its fuel and accounts for almost half of world oil consumption, the transport sector faces a challenging future, given its dependence on oil. In this chapter, existing and future options and potentials to reduce greenhouse gases (GHG) are assessed.

GHG emission reduction will be only one of several key issues in transport during the coming decades and will not be the foremost issue in many areas. In developing countries especially, increasing demand for private vehicles is outpacing the supply of transport infrastructure – including both road networks and public transit networks. The result is growing congestion and air pollution,[3] and a rise in traffic fatalities. Further, the predominant reliance on private vehicles for passenger travel is creating substantial societal strains as economically disadvantaged populations are left out of the rapid growth in mobility. In many countries, concerns about transport will likely focus on the local traffic, pollution, safety and equity effects. The global warming issue in transport will have to be addressed in the context of the broader goal of sustainable development.

5.2   Current status[4] and future trends

5.2.1   Transport today

The transport sector plays a crucial and growing role in world energy use and emissions of GHGs. In 2004, transport energy use amounted to 26% of total world energy use and the transport sector was responsible for about 23% of world energy-related GHG emissions (IEA, 2006b). The 1990–2002 growth rate of energy consumption in the transport sector was highest among all the end-use sectors. Of a total of 77 EJ[5] of total transport energy use, road vehicles account for more than three-quarters, with light-duty vehicles and freight trucks having the lion's share (see Table 5.1). Virtually all (95%) of transport energy comes from oil-based fuels, largely diesel (23.6 EJ, or about 31% of total energy) and gasoline (36.4 EJ, 47%). One consequence of this dependence, coupled with the only moderate differences in carbon content of the various

Table 5.1: *World transport energy use in 2000, by mode*

Mode	Energy use (EJ)	Share (%)
Light-duty vehicles (LDVs)	34.2	44.5
2-wheelers	1.2	1.6
Heavy freight trucks	12.48	16.2
Medium freight trucks	6.77	8.8
Buses	4.76	6.2
Rail	1.19	1.5
Air	8.95	11.6
Shipping	7.32	9.5
Total	76.87	100

Source: WBCSD, 2004b.

oil-based fuels, is that the CO_2 emissions from the different transport sub-sectors are approximately proportional to their energy use (Figure 5.1).

Economic development and transport are inextricably linked. Development increases transport demand, while availability of transport stimulates even more development by allowing trade and economic specialization. Industrialization and growing specialization have created the need for large shipments of goods and materials over substantial distances; accelerating globalization has greatly increased these flows.

Urbanization has been extremely rapid in the past century. About 75% of people in the industrialized world and 40% in the developing world now live in urban areas. Also, cities have grown larger, with 19 cities now having a population over 10 million. A parallel trend has been the decentralization of cities – they have spread out faster than they have grown in population, with rapid growth in suburban areas and the rise of 'edge cities' in the outer suburbs. This decentralization has created both a growing demand for travel and an urban pattern that is not easily served by public transport. The result has been a rapid increase in personal vehicles – not only cars but also 2-wheelers – and a declining share of transit. Further, the lower-density development and the greater distances needed to access jobs and services have seen the decline of walking and bicycling as a share of total travel (WBCSD, 2002).

Another crucial aspect of our transport system is that much of the world is not yet motorized because of low incomes. The majority of the world's population does not have access to personal vehicles, and many do not even have access to motorized public transport services of any sort. Thirty-three percent of China's population and 75% of Ethiopia's still did not have access to all-weather transport (e.g., with roads passable

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3   Although congestion and air pollution are also found in developed countries, they are exacerbated by developing country conditions.
4   The primary source for the 'current status' part of this discussion is WBCSD (World Business Council for Sustainable Development) Mobility 2001 (2002), prepared by Massachusetts Institute of Technology and Charles River Associates Incorporated.
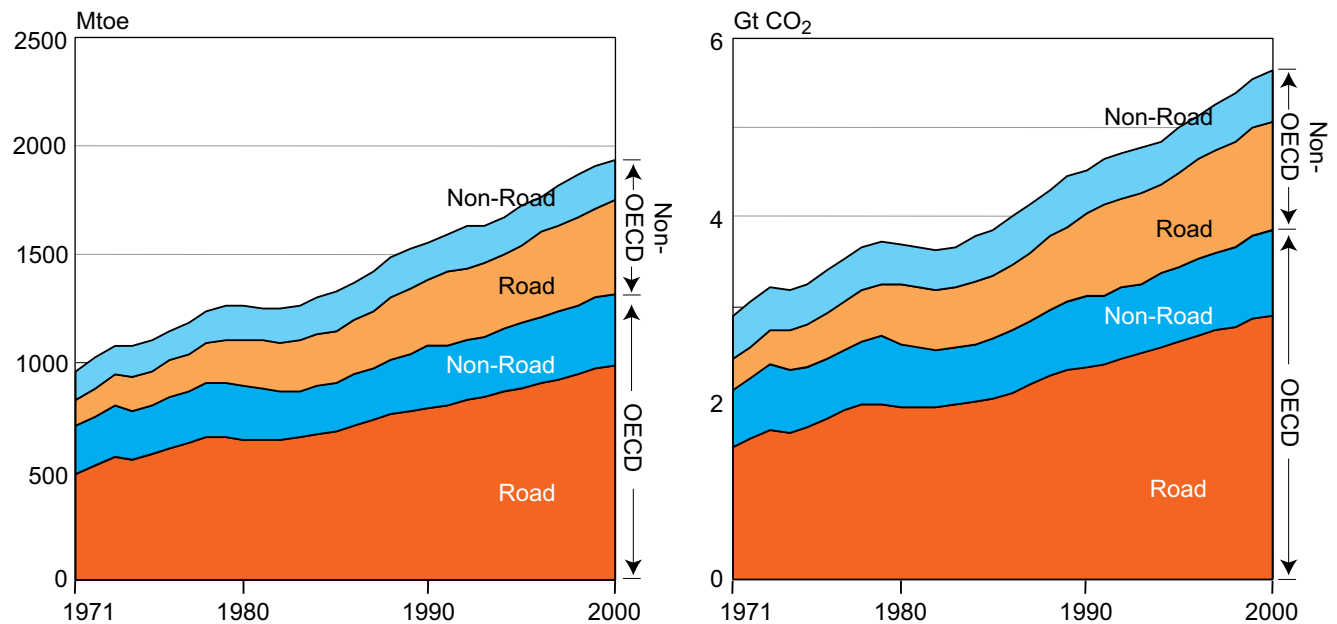5   83 EJ in 2004 (IEA, 2006b).

Figure 5.1: *Energy consumption and CO$_2$ emission in the transport sector*
Source: IEA, 2006c,d

most of the year). Walking more than 10 km/day[6] each way to farms, schools and clinics is not unusual in rural areas of the developing world, particularly sub-Saharan Africa, but also in parts of Asia and Latin America. Commuting by public transport is very costly for the urban poor, taking, for example, 14% of the income of the poor in Manila compared with 7% of the income of the non-poor (World Bank, 1996). If and when these areas develop and their population's incomes rise, the prospects for a vast expansion of motorization and increase in fossil fuel use and GHG emissions is very real. And these prospects are exacerbated by the evidence that the most attractive form of transport for most people as their incomes rise is the motorized personal vehicle, which is seen as a status symbol as well as being faster, flexible, convenient and more comfortable than public transport. Further aggravating the energy and environmental concerns of the expansion of motorization is the large-scale importation of used vehicles into the developing world. Although increased access to activities and services will contribute greatly to living standards, a critical goal will be to improve access while reducing the adverse consequences of motorization, including GHG emissions.

Another factor that has accelerated the increase in transport energy use and carbon emissions is the gradual growth in the size, weight and power of passenger vehicles, especially in the industrialized world. Although the efficiency of vehicle technology has improved steadily over time, much of the benefit of these improvements have gone towards increased power and size at the expense of improved fuel efficiency. For example, the US Environmental Protection Agency has concluded that

the US new Light-duty Vehicle (LDV) fleet fuel economy in 2005 would have been 24% higher had the fleet remained at the weight and performance distribution it had in 1987. Instead, over that time period, it became 27% heavier and 30% faster in 0–60 mph (0–97 km/h) time, and achieved 5% poorer fuel economy (Heavenrich, 2005). In other words, if power and size had been held constant during this period, the fuel consumption rates of light-duty vehicles would have dropped more than 1% per year.

Worldwide travel studies have shown that the average time budget for travel is roughly constant worldwide, with the relative speed of travel determining distances travelled yearly (Schafer, 2000). As incomes have risen, travellers have shifted to faster – and more energy-intensive – modes, from walking and bicycling to public transport to automobiles and, for longer trips, to aircraft. And as income and travel have risen, the percentage of trips made by automobiles has risen. Automobile travel now accounts for 15–30% of total trips in the developing world, but 50% in Western Europe and 90% in the United States. The world auto fleet has grown with exceptional rapidity – between 1950 and 1997, the fleet increased from about 50 million vehicles to 580 million vehicles, five times faster than the growth in population. In China, for example, vehicle sales (not including scooters, motorcycles and locally manufactured rural vehicles) have increased from 2.4 million in 2001 to 5.6 million in 2005[7] and further to 7.2 million in 2006.[8] 2-wheeled scooters and motorcycles have also played an important role in the developing world and in warmer parts of Europe, with a current world fleet of a few hundred million

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6   6.21 miles/day.
7   Automotive News Data Center: http://www.autonews.com/apps/pbcs.dll/search?Category=DATACENTER01archive.
8   China Association of Automobile Manufacturers 2007.1.17: http://60.195.249.78/caam/caam.web/Detail.asp?id=359#

vehicles (WBSCD, 2002). Non-motorized transport continues to dominate the developing world. Even in Latin America and Europe, walking accounts for 20–40% of all trips in many cities (WBCSD, 2002). Bicycles continue to play a major role in much of Asia and scattered cities elsewhere, including Amsterdam and Copenhagen.

Public transport plays a crucial role in urban areas. Buses, though declining in importance against private cars in the industrialized world (EC, 2005; Japanese Statistical Bureau, 2006; US Bureau of Transportation Statistics, 2005) and some emerging economies, are increasing their role elsewhere, serving up to 45% of trips in some areas. Paratransit – primarily minibus jitneys run by private operators – has been rapidly taking market share from the formal public-sector bus systems in many areas, now accounting for 35% of trips in South Africa, 40% in Caracas and Bogota and up to 65% in Manila and other southeast Asian cities (WBCSD, 2002). Heavy rail transit systems are generally found only in the largest, densest cities of the industrialized world and a few of the upper-tier developing world cities.

Intercity and international travel is growing rapidly, driven by growing international investments and reduced trade restrictions, increases in international migration and rising incomes that fuel a desire for increased recreational travel. In the United States, intercity travel already accounts for about one-fifth of total travel and is dominated by auto and air. European and Japanese intercity travel combines auto and air travel with fast rail travel. In the developing world, on the other hand, intercity travel is dominated by bus and conventional rail travel, though air travel is growing rapidly in some areas – 12% per year in China, for example. Worldwide passenger air travel is growing 5% annually – a faster rate of growth than any other travel mode (WBCSD, 2002).

Industrialization and globalization have also stimulated freight transport, which now consumes 35% of all transport energy, or 27 exajoules (out of 77 total) (WBCSD, 2004b). Freight transport is considerably more conscious of energy efficiency considerations than passenger travel because of pressure on shippers to cut costs, however this can be offset by pressure to increase speeds and reliability and provide smaller 'just-in-time' shipments. The result has been that, although the energy-efficiency of specific modes has been increasing, there has been an ongoing movement to the faster and more energy-intensive modes. Consequently, rail and domestic waterways' shares of total freight movement have been declining, while highway's share has been increasing and air freight, though it remains a small share, has been growing rapidly. Some breakdowns:
- Urban freight is dominated by trucks of all sizes.
- Regional freight is dominated by large trucks, with bulk commodities carried by rail and pipelines and some water transport.

- National or continental freight is carried by a combination of large trucks on higher speed roads, rail and ship.
- International freight is dominated by ocean shipping. The bulk of international freight is carried aboard extremely large ships carrying bulk dry cargo (e.g., iron ore), container freight or fuel and chemicals (tankers).
- There is considerable variation in freight transport around the world, depending on geography, available infrastructure and economic development. The United States' freight transport system, which has the highest total traffic in the world, is one in which all modes participate substantially. Russia's freight system, in contrast, is dominated by rail and pipelines, whereas Europe's freight systems are dominated by trucking with a market share of 72% (tkm) in EU-25 countries, while rail's market share is just 16.4% despite its extensive network.[9] China's freight system uses rail as its largest carrier, with substantial contributions from trucks and shipping (EC, 2005).

Global estimates of direct GHG emissions of the transport sector are based on fuel use. The contribution of transport to total GHG emissions was about 23%, with emissions of CO_2 and N_2O amounting to about 6300–6400 $MtCO_2$-eq in 2004. Transport sector CO_2 emissions have increased by around 27% since 1990 (IEA, 2006d). For sub-sectors such as aviation and marine transport, estimates based on more detailed information are available. Estimates of global aviation CO_2 emissions using a consistent inventory methodology have recently been made by Lee *et al.* (2005). These showed an increase by approximately a factor of 1.5 from 331 $MtCO_2$/yr in 1990 to 480 $MtCO_2$/yr in 2000. For seagoing shipping, fuel usage has previously been derived from energy statistics (e.g., Olivier *et al.*, 1996; Corbett *et al.*, 1999; Endresen *et al.*, 2003). More recently, efforts have been committed to constructing inventories using activity-based statistics on shipping movements (Corbett and Köhler, 2003; Eyring *et al.*, 2005a). This has resulted in a substantial discrepancy. Estimated CO_2 emissions vary accordingly. This has prompted debate over inventory methodologies in the literature (Endresen *et al.*, 2004; Corbett and Köhler, 2004). It is noteworthy that the NO_x emissions estimates also vary strongly between the different studies (Eyring *et al.*, 2005a).

5.2.2   Transport in the future

There seems little doubt that, short of worldwide economic collapse, transport activity will continue to grow at a rapid pace for the foreseeable future. However, the shape of that demand and the means by which it will be satisfied depend on several factors.

First, it is not clear whether oil can continue to be the dominant feedstock of transport. There is an on-going debate about the date when conventional oil production will peak, with many arguing that this will occur within the next few decades

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9   This rather small share is the result of priority given to passenger transport and market fragmentation between rival national rail systems.

Box 5.1: Non-CO$_2$ climate impacts

When considering the mitigation potential for the transport sector, it is important to understand the effects that it has on climate change. Whilst the principal GHG emitted is CO$_2$, other pollutants and effects may be important and control/mitigation of these may have either technological or operational trade-offs.

Individual sectors have not been studied in great detail, with the exception of aviation. Whilst surface vehicular transport has a large fraction of global emissions of CO$_2$, its radiative forcing (RF) impact is little studied. Vehicle emissions of NO$_x$, VOCs and CO contribute to the formation of tropospheric O$_3$, a powerful GHG; moreover, black carbon and organic carbon may affect RF from this sector. Shipping has a variety of associated emissions, similar in many respects to surface vehicular transport. One of shipping's particular features is the observed formation of low-level clouds ('ship-tracks'), which has a negative RF effect. The potential coverage of these clouds and its associated RF is poorly studied, but one study estimates a negative forcing of 0.110 W/m^2 (Capaldo *et al.*, 1999), which is potentially much larger than its positive forcing from CO$_2$ and it is possible that the overall forcing from shipping may be negative, although this requires more study. However, a distinction should be drawn between RF and an actual climate effect in terms of global temperature change or sea-level rise; the latter being much more complicated to estimate.

Non-CO$_2$ emissions (CH$_4$ and N$_2$O) from road transport in major Annex I parties are listed in UNFCC GHG inventory data. The refrigerant banks and emission trend of F-gases (CFC-12 + HFC-134a) from air-conditioning are reported in the recent IPCC special report on Safeguarding the Ozone Layer and the Global Climate System (IPCC, 2005). Since a rapid switch from CFC-12 to HFC-134a, which has a much lower GWP index, is taking place, the total amount of F-gases is increasing due to the increase in vehicles with air-conditioning, but total emission in CO$_2$-eq is decreasing and forecasted to continue to decrease. Using the recent ADEME data (2006) on F-gas emissions, the shares of emissions from transport sectors for CO$_2$, CH$_4$, N$_2$O and F-gases (CFC-12 + HFC-134a+HCFC-22) are:

	CO$_2$ (%)	CH$_4$ (%)	N$_2$O (%)	F-gas (%)
USA	88.4	0.2	2.0	8.9
Japan	96.0	0.1	2.5	1.4
EU	95.3	0.3	2.8	1.7

Worldwide F-gas emissions in 2003 were reported to be 610 MtCO$_2$-eq in IPCC (2005), but more recent ADEME data (ADEME, 2006) was about 310 Mt CO$_2$-eq (CFC-12 207, HFC-134a 89, HCFC-22 10 MtCO$_2$-eq), which is about 5% of total transport CO$_2$ emission. It can be seen that non-CO$_2$ emissions from the transport sector are considerably smaller than the CO$_2$ emissions. Also, air-conditioning uses significant quantities of energy, with consequent CO$_2$ emissions from the fuel used to supply this energy. Although this depends strongly on the climate conditions, it is reported to be 2.5–7.5% of vehicle energy consumption (IPCC, 2005).

Aviation has a larger impact on radiative forcing than that from its CO$_2$ forcing alone. This was estimated for 1992 and a range of 2050 scenarios by IPCC (1999) and updated for 2000 by Sausen *et al.* (2005) using more recent scientific knowledge and data. Aviation emissions impact radiative forcing in positive (warming) and negative (cooling) ways as follows: CO$_2$ (+25.3 mW/m^2); O$_3$ production from NO$_x$ emissions (+21.9 mW/m^2); ambient CH$_4$ reduction as a result of NO$_x$ emissions (−10.4 mW/m^2); H$_2$O (+2.0 mW/m^2); sulphate particles (−3.5 mW/m^2); soot particles (+2.5 mW/m^2); contrails (+10.0 mW/m^2); cirrus cloud enhancement (10–80 mW/m^2). These effects result in a total aviation radiative forcing for 2000 of 47.8 mW/m^2, excluding cirrus cloud enhancement, for which no best estimate could be made, as was the case for IPCC (1999). Forster et al. (2007) assumed that aviation radiative forcing (0.048 W/m^2 in 2000, which excludes cirrus) to have grown by no more that 10% between 2000 and 2005. Forster et al. (2007) estimate a total net anthropogenic radiative forcing in 2005 of 1.6 W/m^2 (range 0.6–2.4 W/m^2). Aviation therefore accounts for around 3% of the anthropogenic radiative forcing in 2005 (range 2–8%). This 90% confidence range is skewed towards lower percentages and does not account for uncertainty in the aviation forcings.

(though others, including some of the major multinational oil companies, strongly oppose this view). Transport can be fuelled by multiple alternative sources, beginning with liquid fuels from unconventional oil (very heavy oil, oil sands and oil shale), natural gas or coal, or biomass. Other alternatives include gaseous fuels such as natural gas or hydrogen and electricity, with both hydrogen and electricity capable of being produced from a variety of feedstocks. However, all of these alternatives are costly, and several – especially liquids from fossil resources – can increase GHG emissions significantly without carbon sequestration.
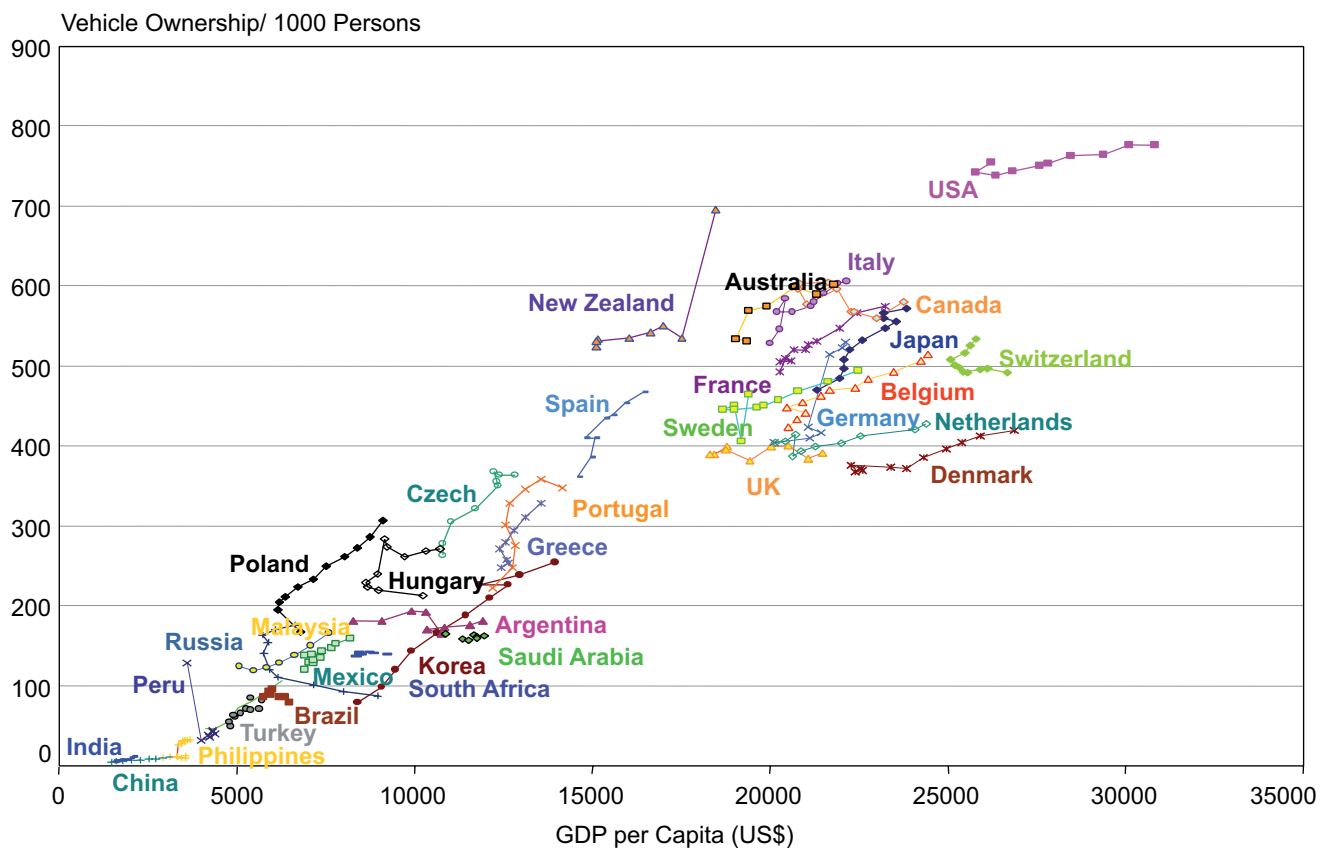
Figure 5.2: *Vehicle ownership as a function of per capita income*

Note: plotted years vary by country depending on data availability.

Data source: World Bank, 2004.

Second, the growth rate and shape of economic development, the primary driver of transport demand, is uncertain. If China and India as well as other Asian countries continue to rapidly industrialize, and if Latin America and Africa fulfil much of their economic potential, transport demand will grow with extreme rapidity over the next several decades. Even in the most conservative economic scenarios though, considerable growth in travel is likely.

Third, transport technology has been evolving rapidly. The energy efficiency of the different modes, vehicle technologies, and fuels, as well as their cost and desirability, will be strongly affected by technology developments in the future. For example, although hybrid electric drive trains have made a strong early showing in the Japanese and US markets, their ultimate degree of market penetration will depend strongly on further cost reductions. Other near-term options include the migration of light-duty diesel from Europe to other regions. Longer term opportunities requiring more advanced technology include new biomass fuels beyond those made from sugar cane in Brazil and corn in the USA, fuel cells running on hydrogen and battery-powered electric vehicles.

Fourth, as incomes in the developing nations grow, transport infrastructure will grow rapidly. Current trends point towards

growing dependence on private cars, but other alternatives exist (as demonstrated by cities such as Curitiba and Bogota with their rapid bus transit systems). Also, as seen in Figure 5.2, the intensity of car ownership varies widely around the world even when differences in income are accounted for, so different countries have made very different choices as they have developed. The future choices made by both governments and travellers will have huge implications for future transport energy demand and CO_2 emissions in these countries.

Most projections of transport energy consumption and GHG emissions have developed Reference Cases that try to imagine what the future would look like if governments essentially continued their existing policies without adapting to new conditions. These Reference Cases establish a baseline against which changes caused by new policies and measures can be measured, and illustrate the types of problems and issues that will face governments in the future.

Two widely cited projections of world transport energy use are the Reference Cases in the ongoing world energy forecasts of the United States Energy Information Administration, 'International Energy Outlook 2005' (EIA, 2005) and the International Energy Agency, World Energy Outlook 2004 (IEA, 2004a). A recent study by the World Business Council on
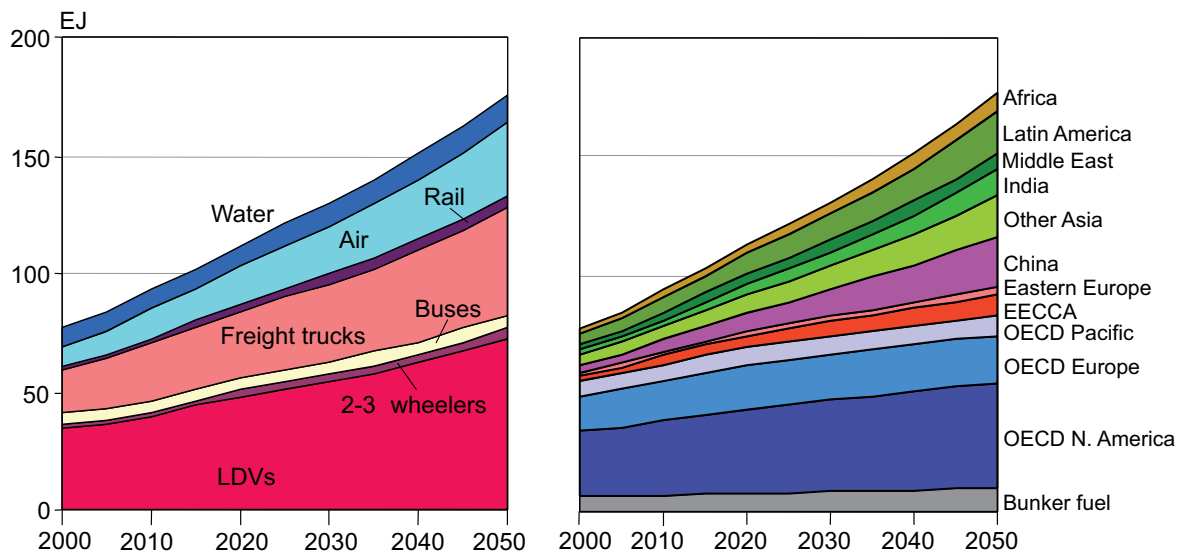
Figure 5.3: *Projection of transport energy consumption by region and mode*
Source: WBCSD, 2004a.

Sustainable Development, 'Mobility 2030', also developed a projection of world transport energy use. Because the WBCSD forecast was undertaken by IEA personnel (WBCSD, 2004b), the WEO 2004 and Mobility 2030 forecasts are quite similar. The WEO 2006 (IEA, 2006b) includes higher oil price assumptions than previously. Its projections therefore tend to be somewhat lower than the two other studies.

The three forecasts all assume that world oil supplies will be sufficient to accommodate the large projected increases in oil demand, and that world economies continue to grow without significant disruptions. With this caveat, all three forecast robust growth in world transport energy use over the next few decades, at a rate of around 2% per year. This means that transport energy use in 2030 will be about 80% higher than in 2002 (see Figure 5.3). Almost all of this new consumption is expected to be in petroleum fuels, which the forecasts project will remain between 93% and slightly over 95% of transport fuel use over the period. As a result, CO_2 emissions will essentially grow in lockstep with energy consumption (see Figure 5.4).

Another important conclusion is that there will be a significant regional shift in transport energy consumption, with the emerging economies gaining significantly in share (Figure 5.3). EIA's International Energy Outlook 2005, as well as the IEA, projects a robust 3.6% per year growth rate for these economies, while the IEA's more recent WEO 2006 projects transport demand growth of 3.2%. In China, the number of cars has been growing at a rate of 20% per year, and personal travel has increased by a factor of five over the past 20 years. At its projected 6% rate of growth, China's transport energy use would nearly quadruple between 2002 and 2025, from 4.3 EJ in 2002 to 16.4 EJ in 2025. China's neighbour India's transport energy is projected to grow at 4.7% per year during this period and countries such as Thailand, Indonesia, Malaysia and Singapore

will see growth rates above 3% per year. Similarly, the Middle East, Africa and Central and South America will see transport energy growth rates at or near 3% per year. The net effect is that the emerging economies' share of world transport energy use would grow in the EIA forecasts from 31% in 2002 to 43% in 2025. In 2004, the transport sector produced 6.2 $GtCO_2$ emissions (23% of world energy-related CO_2 emissions). The share of Non-OECD countries is 36% now and will increase rapidly to 46% by 2030 if current trends continue.

In contrast, transport energy use in the mature market economies is projected to grow more slowly. EIA forecasts 1.2% per year and IEA forecasts 1.3% per year for the OECD nations. EIA projects transport energy in the United States to grow at 1.7% per year, with moderate population and travel growth and only modest improvement in efficiency. Western Europe's transport energy is projected to grow at a much slower 0.4% per year, because of slower population growth, high fuel taxes and significant improvements in efficiency. IEA projects a considerably higher 1.4% per year for OECD Europe. Japan, with an aging population, high taxes and low birth rates, is projected to grow at only 0.2% per year. These rates would lead to 2002–2025 increases of 46%, 10% and 5%, for the USA, Western Europe and Japan, respectively. These economies' share of world transport energy would decline from 62% in 2002 to 51% in 2025.

The sectors propelling worldwide transport energy growth are primarily light-duty vehicles, freight trucks and air travel. The Mobility 2030 study projects that these three sectors will be responsible for 38, 27 and 23%, respectively, of the total 100 EJ growth in transport energy that it foresees in the 2000–2050 period. The WBCSD/SMP reference case projection indicates that the number of LDVs will grow to about 1.3 billion by 2030 and to just over 2 billion by 2050, which is almost three times
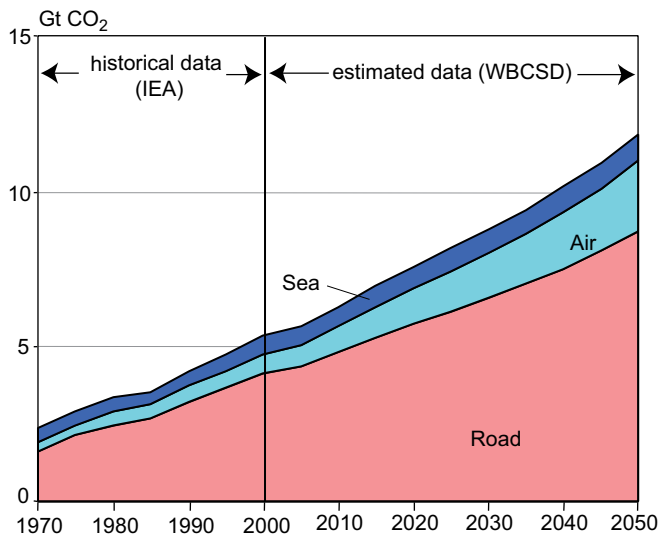
Figure 5.4: *Historical and projected CO$_2$ emission from transport by modes, 1970–2050*

Source: IEA, 2005; WBCSD, 2004b.

Syndrome) during this period, and is currently growing at 5.9% per year. These figures disguise regional differences in growth rate: for example, Europe-Asia/Pacific traffic grew at 12.2% and North American domestic traffic grew at 2.6% per year in 2005. ICAO's outlook for the future forecasts a passenger traffic demand growth of 4.3% per year to 2020. Industry forecasts offer similar prospects for growth: the Airbus Global Market Forecast (Airbus, 2004) and Boeing Current Market Outlook (Boeing, 2006) suggest passenger traffic growth trends of 5.3% and 4.9% respectively, and freight trends at 5.9% and 6.1% respectively over the next 20 or 25 years. In summary, these forecasts and others predict a global average annual passenger traffic growth of around 5% – passenger traffic doubling in 15 years – with freight traffic growing at a faster rate that passenger traffic, although from a smaller base.

The primary energy source for civil aviation is kerosene. Trends in energy use from aviation growth have been modelled using the Aero2K model, using unconstrained demand growth forecasts from Airbus and UK Department of Trade and Industry. The model results suggest that by 2025 traffic will increase by a factor of 2.6 from 2002, resulting in global aviation fuel consumption increasing by a factor of 2.1 (QinetiQ, 2004). Aero2k model results suggest that aviation emissions were approximately 492 MtCO$_2$ and 2.06 MtNO$_x$ in 2002 and will increase to 1029 and 3.31 Mt respectively by 2025.

higher than the present level (Figure 5.5). Nearly all of this increase will be in the developing world.

Aviation

Civil aviation is one of the world's fastest growing transport means. ICAO (2006) analysis shows that aviation scheduled traffic (revenue passenger-km, RPK) has grown at an average annual rate of 3.8% between 2001 and 2005 despite the downturn from the terrorist attacks and SARS *(Severe Acute Respiratory*

Several organizations have constructed scenarios of aviation emissions to 2050 (Figure 5.6), including:
- IPCC (1999) under various technology and GDP assumptions (IS92a, e and c). Emissions were most strongly affected by
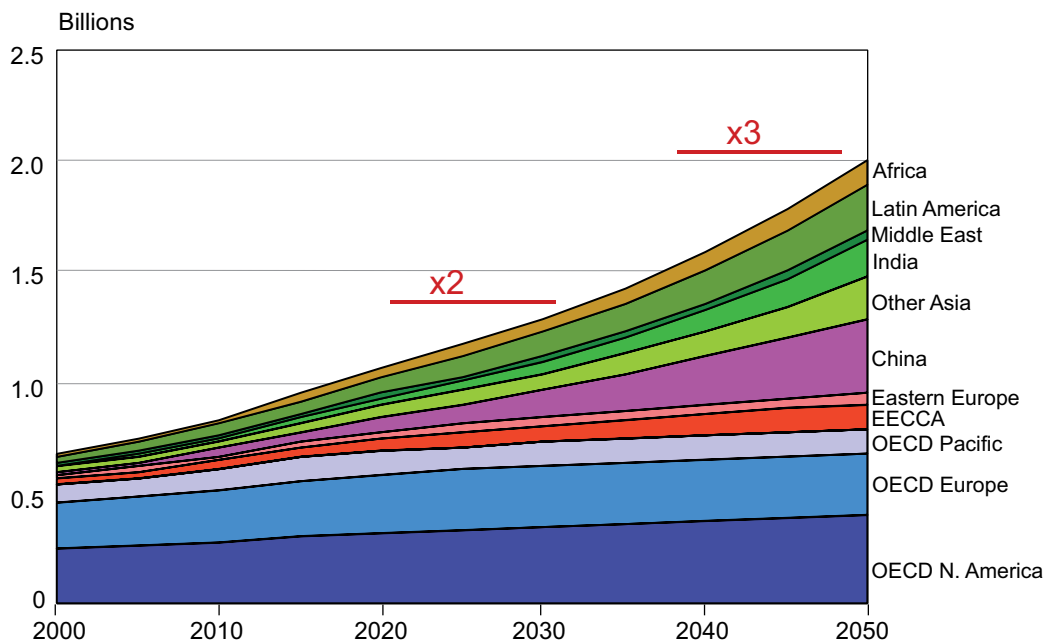

Figure 5.5: *Total stock of light-duty vehicles by region*
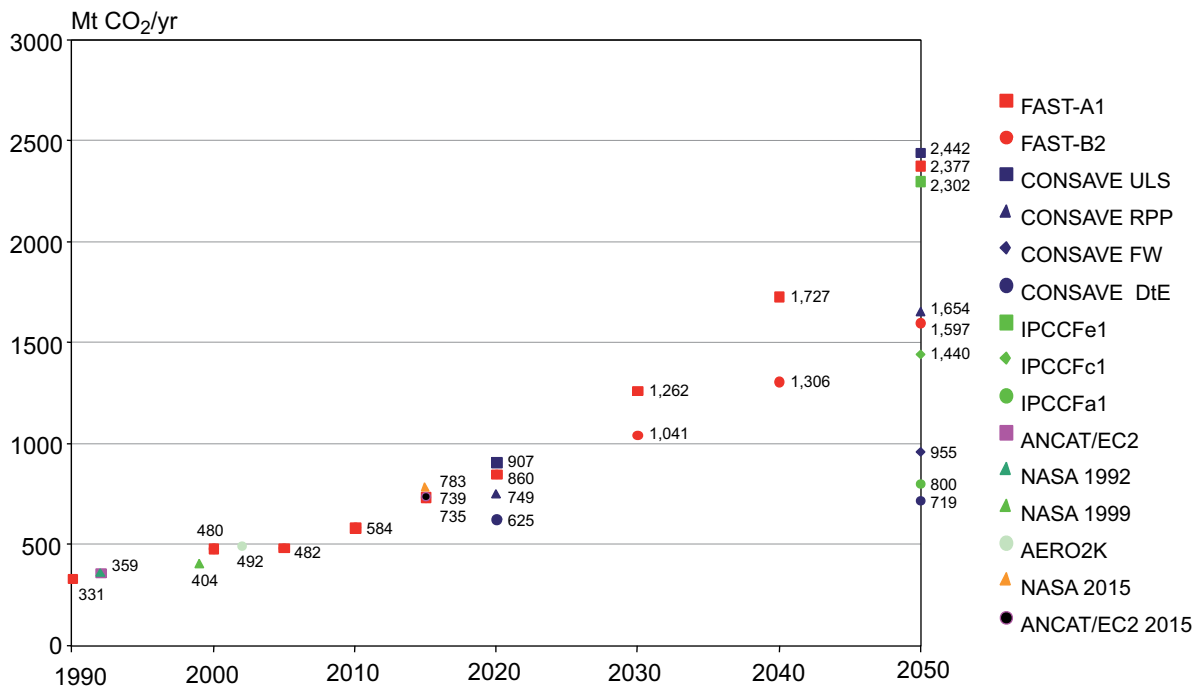
Source: WBCSD, 2004a.

Figure 5.6: *Comparison of global CO$_2$ emissions of civil aviation, 1990–2050*

the GDP assumptions, with technology assumptions having only a second order effect;

- CONSAVE 2050, a European project has produced further 2050 scenarios (Berghof *et al.*, 2005). Three of the four CONSAVE scenarios are claimed to be broadly consistent with IPCC SRES scenarios A1, A2 and B1. The results were not greatly different from those of IPCC (1999);
- Owen and Lee (2005) projected aviation emissions for years 2005 through to 2020 by using ICAO-FESG forecast statistics of RPK (FESG, 2003) and a scenario methodology applied thereafter according to A1 and B2 GDP assumptions similarly to IPCC (1999).

The three estimates of civil aviation CO$_2$ emissions in 2050 from IPCC (1999) show an increase by factors of 2.3, 4.0 and 6.4 over 1992; CONSAVE (Berghof *et al.*, 2005) four scenarios indicate increases of factors of 1.5, 1.9, 3.4 and 5.0 over 2002 emissions (QinetiQ, 2004); and FAST A1 and B2 results (Owen and Lee, 2006) indicate increases by factors of 3.3 and 5.0 over 2000 emissions.

Shipping
Around 90% of global merchandise is transported by sea. For many countries sea transport represents the most important mode of transport for trade. For example, for Brazil, Chile and Peru over 95% of exports in volume terms (nearly 75% in value terms) are seaborne. Economic growth and the increased integration in the world economy of countries from far-east and southeast Asia is contributing to the increase of international marine transport. Developments in China are now considered to be one of the most important stimulus to growth for the tanker, chemical, bulk and container trades (OECD, 2004b).

World seaborne trade in ton-miles recorded another consecutive annual increase in 2005, after growing by 5.1%. Crude oil and oil products dominate the demand for shipping services in terms of ton-miles (40% in 2005) (UN, 2006), indicating that demand growth will continue in the future. During 2005, the world merchant fleet expanded by 7.2%. The fleets of oil tankers and dry bulk carriers, which together make up 72.9% of the total world fleet, increased by 5.4%. There was a 13.3% increase in the container ship fleet, whose share of total fleet is 12%.

Eyring *et al.* (2005a) provided a set of carbon emission projections out to 2050 (Eyring *et al.*, 2005b) based upon four traffic demand scenarios corresponding to SRES A1, A2, B1, B2 (GDP) and four technology scenarios which are summarized below in Table 5.2.

The resultant range of potential emissions is shown in Figure 5.7.

5.3 Mitigation technologies and strategies

Many technologies and strategies are at hand to reduce the growth or even, eventually, reverse transport GHG emissions. Most of the technology options discussed here were mentioned in the TAR. The most promising strategy for the near term is incremental improvements in current vehicle technologies. Advanced technologies that provide great promise include greater use of electric-drive technologies, including hybrid-

Table 5.2: *Summary of shipping technology scenarios*

Technology scenario 1 (TS1) – 'Clean scenario'	Technology scenario 2 (TS2) – 'Medium scenario'	Technology scenario 3 (TS3) – 'IMO compliant scenario'	Technology scenario 4 (TS4) – 'BAU'
Low S content fuel (1%/0.5%), aggressive NO_x reductions	Relatively low S content fuel (1.8%/1.2%), moderate NO_x reduction	High S content fuel (2%/2%), NO_x reductions according to IMO stringency only	High S content fuel (2%/2%), NO_x reductions according to IMO stringency only
Fleet = 75% diesel, 25% alternative plant	Fleet = 75% diesel, 25% alternative plant	Fleet = 75% diesel, 25% alternative plant	Fleet = 100% diesel

Note: The fuel S percentages refer to values assumed in (2020/2050).

Source: Eyring et al. 2005b.

electric power trains, fuel cells and battery electric vehicles. The use of alternative fuels such as natural gas, biofuels, electricity and hydrogen, in combination with improved conventional and advanced technologies; provide the potential for even larger reductions.

Even with all these improved technologies and fuels, it is expected that petroleum will retain its dominant share of transport energy use and that transport GHG emissions will continue to increase into the foreseeable future. Only with sharp changes in economic growth, major behavioural shifts, and/or major policy intervention would transport GHG emissions decrease substantially.

5.3.1　Road transport

GHG emissions associated with vehicles can be reduced by four types of measures:
1. Reducing the loads (weight, rolling and air resistance and accessory loads) on the vehicle, thus reducing the work needed to operate it;
2. Increasing the efficiency of converting the fuel energy to work, by improving drive train efficiency and recapturing energy losses;

3. Changing to a less carbon-intensive fuel; and
4. Reducing emissions of non-CO_2 GHGs from vehicle exhaust and climate controls.

The loads on the vehicle consist of the force needed to accelerate the vehicle, to overcome inertia; vehicle weight when climbing slopes; the rolling resistance of the tyres; aerodynamic forces; and accessory loads. In urban stop-and-go driving, aerodynamic forces play little role, but rolling resistance and especially inertial forces are critical. In steady highway driving, aerodynamic forces dominate, because these forces increase with the square of velocity; aerodynamic forces at 90 km/h[10] are four times the forces at 45 km/h. Reducing inertial loads is accomplished by reducing vehicle weight, with improved design and greater use of lightweight materials. Reducing tyre losses is accomplished by improving tyre design and materials, to reduce the tyres' rolling resistance coefficient, as well as by maintaining proper tyre pressure; weight reduction also contributes, because tyre losses are a linear function of vehicle weight. And reducing aerodynamic forces is accomplished by changing the shape of the vehicle, smoothing vehicle surfaces, reducing the vehicle's cross-section, controlling airflow under the vehicle and other measures. Measures to reduce the heating and cooling needs of the passengers, for example by changing window glass to reflect incoming solar radiation, are included in the group of measures.

Increasing the efficiency with which the chemical energy in the fuel is transformed into work, to move the vehicle and provide comfort and other services to passengers, will also reduce GHG emissions. This includes measures to improve engine efficiency and the efficiency of the rest of the drive train and accessories, including air conditioning and heating. The range of measures here is quite great; for example, engine efficiency can be improved by three different kinds of measures, increasing thermodynamic efficiency, reducing frictional losses and reducing pumping losses (these losses are the energy needed to pump air and fuel into the cylinders and push out the exhaust) and each kind of measure can be addressed by a great number of design, material and technology changes. Improvements in transmissions can reduce losses in the transmission itself and help engines to operate in their most
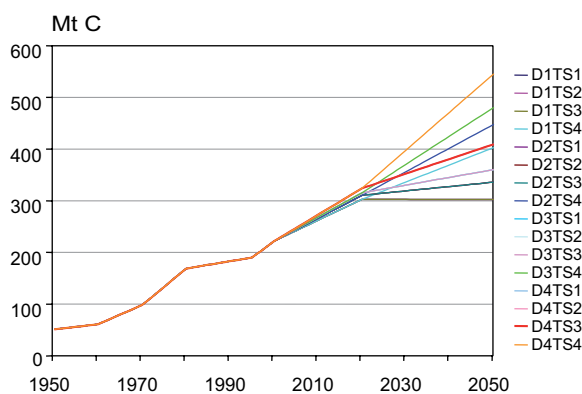

Figure 5.7: *Historical and projected CO₂ emissions of seagoing shipping, 1990-2050*

Note: See Table 5.2 for the explanation of the scenarios.

Source: adapted from Eyring et al., 2005a,b.

10　1 km/h = 0.621 mph

efficient modes. Also, some of the energy used to overcome inertia and accelerate the vehicle – normally lost when the vehicle is slowed, to aerodynamic forces and rolling resistance as well to the mechanical brakes (as heat) – may be recaptured as electrical energy if regenerative braking is available (see the discussion of hybrid electric drive trains).

The use of different liquid fuels, in blends with gasoline and diesel or as 'neat fuels' require minimal or no changes to the vehicle, while a variety of gaseous fuels and electricity would require major changes. Alternative liquid fuels include ethanol, biodiesel and methanol, and synthetic gasoline and diesel made from natural gas, coal, or other feedstocks. Gaseous fuels include natural gas, propane, dimethyl ether (a diesel substitute) and hydrogen. Each fuel can be made from multiple sources, with a wide range of GHG emission consequences. In evaluating the effects of different fuels on GHG emissions, it is crucial to consider GHG emissions associated with fuel production and distribution in addition to vehicle tailpipe emissions (see the section on well-to-wheels analysis). For example, the consumption of hydrogen produces no emissions aside from water directly from the vehicle, but GHG emissions from hydrogen production can be quite high if the hydrogen is produced from fossil fuels (unless the carbon dioxide from the hydrogen production is sequestered).

The sections that follow discuss a number of technology, design and fuel measures to reduce GHG emissions from vehicles.

5.3.1.1   *Reducing vehicle loads*

Lightweight materials

A 10% weight reduction from a total vehicle weight can improve fuel economy by 4–8%, depending on changes in vehicle size and whether or not the engine is downsized. There are several ways to reduce vehicle weight; including switching to high strength steels (HSS), replacing steel by lighter materials such as Al, Mg and plastics, evolution of lighter design concepts and forming technologies. The amount of lighter materials in vehicles has been progressively increasing over time, although not always resulting in weight reductions and better fuel economy if they are used to increase the size or performance of the vehicle. In fact, the average weight of a vehicle in the USA and Japan has increased by 10–20% in the last 10 years (JAMA, 2002; Haight, 2003), partly due to increased concern for safety and customers' desire for greater comfort.

Steel is still the main material used in vehicles, currently averaging 70% of kerb weight. Aluminium usage has grown to roughly 100 kg per average passenger car, mainly in the engine, drive train and chassis in the form of castings and forgings. Aluminium is twice as strong as an equal weight of steel, allowing the designer to provide strong, yet lightweight structures. Aluminium use in body structures is limited, but there are a few commercial vehicles with all Al bodies (e.g., Audi's A2 and A8). Where more than 200 kg of Al is used and secondary weight reductions are gained by down-sizing the engine and suspension – more than 11–13% weight reduction can be achieved. Ford's P2000 concept car[11] has demonstrated that up to 300 kg of Al can be used in a 900 kg vehicle.

Magnesium has a density of 1.7–1.8 g/cc[12], about 1/4 that of steel, while attaining a similar (volumetric) strength. Major hurdles for automobile application of magnesium are its high cost and performances issues such as low creep strength and contact corrosion susceptibility. At present, the use of magnesium in vehicle is limited to only 0.1–0.3% of the whole weight. However, its usage in North American-built family vehicles has been expanding by 10 to 14% annually in recent years. Aluminium has grown at 4–6%; plastics by 1–1.8%; and high strength steels by 3.5–4%. Since the amount of energy required to produce Mg and also Al is large compared with steel, LCA analysis is important in evaluating these materials' potential for CO_2 emission reduction (Helms and Lambrecht, 2006). Also, the extent of recycling is an important issue for these metals.

The use of plastics in vehicles has increased to about 8% of total vehicle weight, which corresponds to 100-120 kg per vehicle. The growth rate of plastics content has been decreasing in recent years however, probably due to concerns about recycling, given that most of the plastic goes to the automobile shredder residue (ASR) at the end of vehicle life. Fibre-reinforced plastic (FRP) is now widely used in aviation, but its application to automobiles is limited due to its high cost and long processing time. However, its weight reduction potential is very high, maybe as much as 60%. Examples of FRP structures manufactured using RTM (resin transfer method) technology are wheel housings or entire floor assemblies. For a compact-size car, this would make it possible to reduce the weight; of a floor assembly (including wheel housings) by 60%, or 22 kg per car compared to a steel floor assembly. Research examples of plastics use in the chassis are leaf or coil springs manufactured from fibre composite plastic. Weight reduction potentials of up to 63% have been achieved in demonstrators using glass and/or carbon fibre structures (Friedricht, 2002).

Aside from the effect of the growing use of non-steel materials, the reduction in the average weight of steel in a car is driven by the growing shift from conventional steels to high strength steels (HSS). There are various types of HSS, from relatively low strength grade (around 400 MPa) such as solution-hardened and precipitation-hardened HSS to very high strength grade (980–1400 MPa) such as TRIP steel and tempered martensitic HSS. At present, the average usage per vehicle of HSS is 160 kg (11% of whole weight) in the USA

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11 SAE International (Society of Automotive Engineers): The aluminum angle, automotive engineering on-line, http://www.sae.org/automag/metals/10.htm.
12 Specific gravity 1738

and 75 kg (7%) in Japan. In the latest Mercedes A-class vehicle, HSS comprises 67% of body structure weight. The international ULSAB-AVC project (Ultra Light Steel Auto Body – Advanced Vehicle Concept) investigated intensive use of HSS, including advanced HSS, and demonstrated that using HSS as much as possible can reduce vehicle weight by 214 kg (–19%) and 472 kg (–32%) for small and medium passenger cars respectively. In this concept, the total usage of HSS in body and closures structures is 280–330 kg, of which over 80% is advanced HSS (Nippon Steel, 2002).

Since heavy-duty vehicles such as articulated trucks are much heavier than passenger vehicles, their weight reduction potential is much larger. It is possible to reduce the weight of tractor and trailer combination by more than 3000 kg by replacing steel with aluminium (EAA, 2001).

Aerodynamics improvement

Improvements have been made in the aerodynamic performance of vehicles over the past decade, but substantial additional improvements are possible. Improvement in aerodynamic performance offers important gains for vehicles operating at higher speeds, e.g., long-distance trucks and light-duty vehicles operating outside congested urban areas. For example a 10% reduction in the coefficient of drag (C_D) of a medium sized passenger car would yield only about a 1% reduction in average vehicle forces on the US city cycle (with 31.4 km/h average speed), whereas the same drag reduction on the US highway cycle, with average speed of 77.2 km/h, would yield about a 4% reduction in average forces.[13] These reductions in vehicle forces translate reasonably well into similar reductions in fuel consumption for most vehicles, but variations in engine efficiency with vehicle force may negate some of the benefit from drag reduction unless engine power and gearing are adjusted to take full advantage of the reduction.

For light-duty vehicles, styling and functional requirements (especially for light-duty trucks) may limit the scope of improvement. However, some vehicles introduced within the past five years demonstrate that improvement potential still remains for the fleet. The Lexus 430, a conservatively styled sedan, attains a C_D (coefficient of aerodynamic drag) of 0.26 versus a fleet average of over 0.3 for the US passenger car fleet. Other fleet-leading examples are:
- Toyota Prius, Mercedes E-class sedans, 0.26
- Volkswagen Passat, Mercedes C240, BMW 320i, 0.27

For light trucks, General Motors' 2005 truck fleet has reduced average C_D by 5–7% by sealing unnecessary holes in the front of the vehicles, lowering their air dams, smoothing their undersides and so forth (SAE International, 2004).

The current generation of heavy-duty trucks in the United States has average C_Ds ranging from 0.55 for tractor-trailers to 0.65 for tractor-tandem trailers. These trucks generally have spoilers at the top of their cabs to reduce air drag, but substantial further improvements are available. C_D reductions of about 0.15, or 25% or so (worth about 12% reduced fuel consumption at a steady 65 mph[14]), can be obtained with a package of base flaps (simple flat plates mounted on the edges of the back end of a trailer) and side skirts (McCallen *et al.*, 2004). The US Department of Energy's 2012 research goals for heavy-duty trucks (USDOE, 2000)[15] include a 20% reduction (from a 2002 baseline, with C_D of 0.625) in aerodynamic drag for a 'class 8' tractor-trailer combination.[16] C_D reductions of 50% and higher, coupled with potential benefits in safety (from better braking and roll and stability control), may be possible with pneumatic (air blowing) devices (Englar, 2001). A complete package of aerodynamic improvements for a heavy-duty truck, including pneumatic blowing, might save about 15–20% of fuel for trucks operating primarily on uncongested highways, at a cost of about 5000 US$ in the near-term, with substantial cost reductions possible over time (Vyas *et al.*, 2002).

The importance of aerodynamic forces at higher speeds implies that reduction of vehicle highway cruising speeds can save fuel and some nations have used speed limits as fuel conservation measures, e.g., the US during the period following the 1973 oil embargo. US tests on nine vehicles with model years from 1988 to 1997 demonstrated an average 17.1% fuel economy loss in driving at 70 mph compared to 55 mph (ORNL, 2006). Recent tests on six contemporary vehicles, including two hybrids, showed similar results – the average fuel economy loss was 26.5% in driving at 80 mph compared to 60 mph, and 27.2% in driving at 70 mph compared to 50 mph (Duoba *et al.*, 2005).

Mobil Air Conditioning (MAC) systems

MAC systems contribute to GHG emissions in two ways by direct emissions from leakage of refrigerant and indirect emissions from fuel consumption. Since 1990 significant progress has been made in limiting refrigerant emissions due to the implementation of the Montreal Protocol. The rapid switch from CFC-12 (GWP 8100) to HFC-134a (GWP 1300) has led to the decrease in the CO_2-eq emissions from about 850 $MtCO_2$-eq in 1990 to 609 $MtCO_2$-eq in 2003, despite the continued growth of the MAC system fleet (IPCC, 2005).

Refrigerant emissions can be decreased by using new refrigerants with a much lower GWP, such as HFC-152a or CO_2, restricting refrigerant sales to certified service professionals and better servicing and disposal practices. Although the feasibility of CO_2 refrigerant has been demonstrated, a number of technical hurdles have still to be overcome.

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13 The precise value would depend on the value of the initial C_D as well as other aspects of the car's design.
14 1 mph = 1.6 km/h
15 Http://www.eere.energy.gov/vehiclesandfuels/about/partnerships/21centurytruck/21ct_goals.shtml.
16 These are heavy-duty highway trucks with separate trailers, but less than 5 axles – the standard long-haul truck in the U.S.

Since the energy consumption for MAC is estimated to be 2.5–7.5% of total vehicle energy consumption, a number of solutions have to be developed in order to limit the energy consumption of MAC, such as improvements of the design of MAC systems, including the control system and airflow management.

5.3.1.2   Improving drive train efficiency

Advanced Direct Injection Gasoline / Diesel Engines and transmissions.

New engine and transmission technologies have entered the light-duty vehicle fleets of Europe, the USA and Japan, and could yield substantial reductions in carbon emissions if more widely used.

Direct injection diesel engines yielding about 35% greater fuel economy than conventional gasoline engines are being used in about half the light-duty vehicles being sold in European markets, but are little used in Japan and the USA (European taxes on diesel fuel generally are substantially lower than on gasoline, which boosts diesel share). Euro 4 emission standards were enforced in 2005, with Euro 5 (still undefined) to follow around 2009–2010. These standards, plus Tier 2 standards in the USA, will challenge diesel NO_x controls, adding cost and possibly reducing fuel efficiency somewhat. Euro 4/Tier 2 compliant diesels for light-duty vehicles, obtaining 30% better fuel efficiency than conventional gasoline engines, may cost about 2000–3000 US$ more than gasoline engines (EEA, 2003).

Improvements to gasoline engines include direct injection. Mercedes' M271 turbocharged direct injection engine is estimated to attain 18% reduced fuel consumption, part of which is due to intake valve control and other engine technologies (SAE International, 2003a); cylinder shutoff during low load conditions (Honda Odyssey V6, Chrysler Hemi, GM V8s) (SAE International, 2003a) and improved valve timing and lift controls.

Transmissions are also being substantially improved. Mercedes, GM, Ford, Chrysler, Volkswagen and Audi are introducing advanced 6 and 7 speed automatics in their luxury vehicles, with strong estimated fuel economy improvements ranging from 4–8% over a 4-speed automatic for the Ford/GM 6-speed to a claimed 13% over a manual, plus faster acceleration, for the VW/Audi BorgWarner 6-speed (SAE International, 2003b). If they follow the traditional path for such technology, these transmissions will eventually be rolled into the fleet. Also, continuously variable transmissions (CVTs), which previously had been limited to low power drive trains, are gradually rising in their power-handling capabilities and are moving into large vehicles.

The best diesel engines currently used in heavy-duty trucks are very efficient, achieving peak efficiencies in the 45–46% range (USDOE, 2000). Although recent advances in engine and drive train technology for heavy-duty trucks have focused on emissions reductions, current research programmes in the US Department of Energy are aiming at 10–20% improvements in engine efficiency within ten years (USDOE, 2000), with further improvements of up to 25% foreseen if significant departures from the traditional diesel engine platform can be achieved.

Engines and drive trains can also be made more efficient by turning off the engine while idling and drawing energy from other sources. The potential for reducing idling emissions in heavy-duty trucks is significant. In the USA, a nationwide survey found that, on average, a long-haul truck consumed about 1,600 gallons, or 6,100 litres, per year from idling during driver rest periods. A variety of behavioural and technological practices could be pursued to save fuel. A technological fix is to switch to grid connections or use onboard auxiliary power units during idling (Lutsey *et al*., 2004).

Despite the continued tightening of emissions standards for both light-duty vehicles and freight trucks, there are remaining concerns about the gap between tested emissions and on-road emissions, particularly for diesel engines. Current EU emissions testing uses test cycles that are considerably gentler than seen in actual driving, allowing manufacturers to design drive trains so that they pass emissions tests but 'achieve better fuel efficiency or other performance enhancement at the cost of higher emissions during operation on the road (ECMT, 2006).' Other concerns involve excessive threshold limits demanded of onboard diagnostics systems, aftermarket mechanical changes (replacement of computer chips, disconnection of exhaust gas recirculation systems) and failure to maintain required fluid levels in Selective Catalytic Reduction systems (ECMT, 2006). Similar concerns in the USA led to the phase-in between 2000 and 2004 of a more aggressive driving cycle (the US06 cycle) to emission tests for LDVs; however, the emission limits tied to this cycle were not updated when new Tier 2 emission standards were promulgated, so concerns about onroad emissions, especially for diesels, will apply to the USA as well.

Hybrid drive trains

Hybrid-electric drive trains combine a fuel-driven power source, such as a conventional internal combustion engine (ICE) with an electric drive train – electric motor/generator and battery (or ultracapacitor) - in various combinations.[17] In current hybrids, the battery is recharged only by regenerative braking and engine charging, without external charging from the grid. 'Plug-in hybrids,' which would obtain part of their energy from the electric grid, can be an option but require a larger battery and perhaps a larger motor. Hybrids save energy by:

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17 A hybrid drive train could use an alternative to an electric drive train, for example a hydraulic storage and power delivery system. The U.S. Environmental Protection Agency has designed such a system.

- Shutting the engine down when the vehicle is stopped (and possibly during braking or coasting);
- Recovering braking losses by using the electric motor to brake and using the electricity generated to recharge the battery;
- Using the motor to boost power during acceleration, allowing engine downsizing and improving average engine efficiency;
- Using the motor instead of the engine at low load (in some configurations), eliminating engine operation during its lowest efficiency mode;
- Allowing the use of a more efficient cycle than the standard Otto cycle (in some hybrids);
- Shifting power steering and other accessories to (more efficient) electric operation.

Since the 1998 introduction of the Toyota Prius hybrid in the Japanese market, hybrid electric drive train technology has advanced substantially, expanding its markets, developing in alternative forms that offer different combinations of costs and benefits and improving component technologies and system designs. Hybrids now range from simple belt-drive alternator-starter systems offering perhaps 7 or 8% fuel economy benefit under US driving conditions to 'full hybrids' such as the Prius offering perhaps 40–50% fuel economy benefits[18] (the Prius itself more than doubles the fuel economy average – on the US test – of the combined 2004 US model year compact and medium size classes, although some portion of this gain is due to additional efficiency measures). Also, hybrids may improve fuel efficiency by substantially more than this in congested urban driving conditions, so might be particularly useful for urban taxis and other vehicles making frequent stops. Hybrid sales have expanded rapidly: in the United States, sales were about 7,800 in 2000 and have risen rapidly, to 207,000 in 2005[19]; worldwide hybrid sales were about 541,000 in 2005 (IEA Hybrid Website, 2006).

Improvements made to the Prius since its introduction demonstrate how hybrid technology is developing. For example, the power density of Prius's nickel metal hydride batteries has improved from 600 W/kg[1] in 1998 to 1250 W/kg[1] in 2004 - a 108% improvement. Similarly, the batteries' specific energy has increased 37% during the same period (EEA, 2003). Higher voltage in the 2004 Prius allows higher motor power with reduced electrical losses and a new braking-by-wire system maximizes recapture of braking energy. The 1998 Prius compact sedan attained 42 mpg on the US CAFE cycle, with 0–60 mph acceleration time of 14.5 seconds; the 2004 version is larger (medium size) but attains 55 mpg and a 0–60 of 10.5 seconds. Prius-type hybrid systems will add about 4,000 US$ to the price of a medium sized sedan (EEA, 2003), but continued cost reduction and development efforts should gradually reduce costs.

Hybridization can yield benefits in addition to directly improving fuel efficiency, including (depending on the design) enhanced performance (with reduced fuel efficiency benefits in some designs), less expensive 4-wheel drive systems, provision of electric power for off-vehicle use (e.g., GM Silverado hybrid), and ease of introducing more efficient transmissions such as automated manuals (using the motor to reduce shift shock).

Hybrid drive trains' strong benefits in congested stop-and-go travel mesh well with some heavier-duty applications, including urban buses and urban delivery vehicles. An initial generation of hybrid buses in New York City obtained about a 10% improvement in fuel economy as well as improved acceleration capacity and substantially reduced emissions (Foyt, 2005). More recently, a different design achieved a 45% fuel economy increase in NYC operation (not including summer, where the increase should be lower) (Chandler *et al*., 2006). Fedex has claimed a 57% fuel economy improvement for its E700 diesel hybrid delivery vehicles (Green Car Congress, 2004).

Hybrid applications extend to two and three-wheelers, as well, because these often operate in crowded urban areas in stop-and-go operation. Honda has developed a 50 cc hybrid scooter prototype that offers about a one-third reduction in fuel use and GHG emissions compared to similar 50 cc scooters (Honda, 2004). However, sales of two and three-wheeled vehicles in most markets are extremely price sensitive, so the extent of any potential market for hybrid technology may be quite limited.

Plug-in hybrids, or PHEVs, are a merging of hybrid electric and battery electric. PHEVs get some of their energy from the electricity grid. Plug-in hybrid technology could be useful for both light-duty vehicles and for a variety of medium duty vehicles, including urban buses and delivery vehicles. Substantial market success of PHEV technology is, however, likely to depend strongly on further battery development, in particular on reducing battery cost and specific energy and increasing battery lifetimes.

PHEVs' potential to reduce oil use is clear – they can use electricity to 'fuel' a substantial portion of miles driven. The US Electric Power Research Institute (EPRI, 2001) estimates that 30 km hybrids (those that have the capability to operate up to 30 km solely on electricity from the battery) can substitute electricity for gasoline for approximately 30–40% of miles driven in the USA. With larger batteries and motors, the vehicles could replace even more mileage. However, their potential to reduce GHG emissions more than that achieved by current hybrids depends on their sources of electricity. For regions that rely on relatively low-carbon electricity for off-peak power, e.g., natural gas combined cycle power, GHG reductions over the PHEV's lifecycle will be substantial; in contrast, PHEVs in areas that rely on coal-fired power could have increased lifecycle

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18 Precise values are somewhat controversial because of disagreements about the fuel economy impact of other fuel-saving measures on the vehicles.
19 Based on sales data from http://electricdrive.org/index.php?tg=articles&topics=7 and J.D. Power.
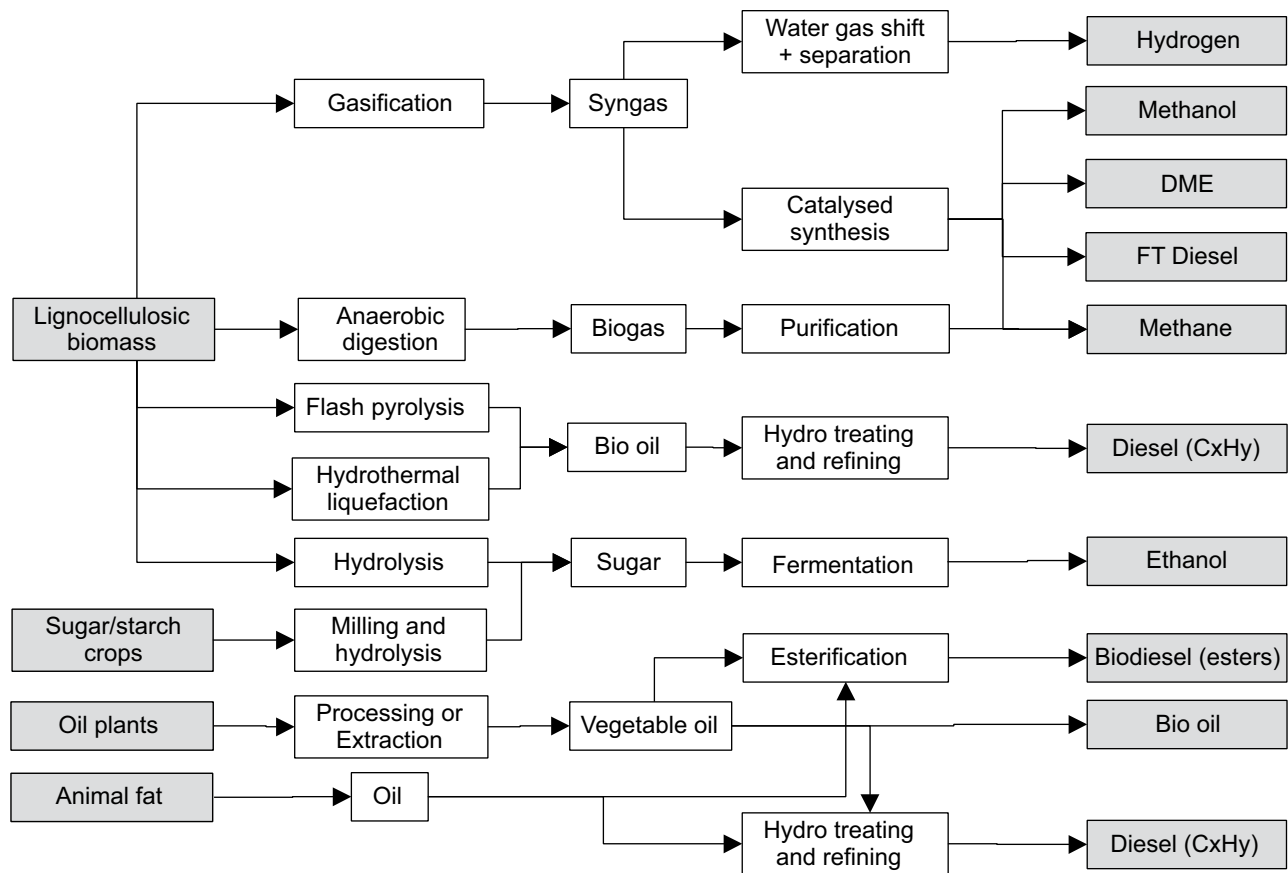
Figure 5.8: *Overview of conversion routes from crops to biofuels*
Source: Adapted from Hamelinck and Faaij, 2006.

carbon emissions. In the long-term, movement to a low-carbon electricity sector could allow PHEVs to play a major role in reducing transport sector GHG emissions.

5.3.1.3　Alternative fuels

Biofuels

The term biofuels describes fuel produced from biomass. A variety of techniques can be used to convert a variety of CO_2 neutral biomass feedstocks into a variety of fuels. These fuels include carbon-containing liquids such as ethanol, methanol, biodiesel, di-methyl esters (DME) and Fischer-Tropsch liquids, as well as carbon-free hydrogen. Figure 5.8 shows some main routes to produce biofuels: extraction of vegetable oils, fermentation of sugars to alcohol, gasification and chemical synthetic diesel, biodiesel and bio oil. In addition, there are more experimental processes, such as photobiological processes that produce hydrogen directly.

Biofuels can be used either 'pure' or as a blend with other automotive fuels. There is a large interest in developing biofuel technologies, not only to reduce GHG emission but more so to decrease the enormous transport sector dependence on imported oil. There are two biofuels currently used in the world for transport purposes – ethanol and biodiesel.

Ethanol is currently made primarily by the fermentation of sugars produced by plants such as sugar cane, sugar beet and corn. Ethanol is used in large quantities in Brazil where it is made from sugar cane, in the USA where it is made from corn, but only in very small quantities elsewhere.

Ethanol is blended with gasoline at concentrations of 5–10% on a volume basis in North America and Europe. In Brazil ethanol is used either in its pure form replacing gasoline, or as a blend with gasoline at a concentration of 20–25%. The production of ethanol fuelled cars in Brazil achieved 96% market share in 1985, but sharply declining shortly thereafter to near zero. Ethanol vehicle sales declined because ethanol producers shifted to sugar production and consumers lost confidence in reliable ethanol supply. A 25% blend of ethanol has continued to be used. With the subsequent introduction of flexfuel cars (see Box 5.2), ethanol fuel sales have increased. However, the sugar cane experience in Brazil will be difficult to replicate elsewhere. Land is plentiful, the sugar industry is highly efficient, the crop residues (bagasse) are abundant and easily used for process energy, and a strong integrated R&D capability has been developed in cane growing and processing.

In various parts of Asia and Africa, biofuels are receiving increasing attention and there is some experience with ethanol-

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Box 5.2 Flexfuel vehicle (FFV)[20]

Particularly in Brazil where there is large ethanol availability as an automotive fuel there has been a substantial increase in sales of flexfuel vehicles (FFV). Flexfuel vehicle sales in Brazil represent about 81% (Nov. 2006) of the market share of light-duty vehicles. The use of FFVs facilitates the introduction of new fuels. The incremental vehicle cost is small, about 100 US$.

The FFVs were developed with systems that allow the use of one or more liquid fuels, stored in the same tank. This system is applied to OTTO cycle engines and enables the vehicles to run on gasoline, ethanol or both in a mixture, according to the fuel availability. The combustion control is done through an electronic device, which identifies the fuel being used and then the engine control system makes the suitable adjustments allowing the running of the engine in the most adequate condition.

One of the greatest advantages of FFVs is their flexibility to choose their fuel depending mainly on price. The disadvantage is that the engine cannot be optimized for the attributes of a single fuel, resulting in foregone efficiency and higher pollutant emissions (though the latter problem can be largely addressed with sophisticated sensors and computer controls, as it is in the USA).

In the USA[21], the number of FFVs is close to 6 million and some US manufacturers are planning to expand their sales. However, unlike in the Brazilian experience, ethanol has not been widely available at fuel stations (other than as a 10% blend) and thus the vehicles rarely fuel with ethanol. Their popularity in the USA is due to special fuel economy credits available to the manufacturer.

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gasoline blending of up to 20%. Ethanol is being produced from sugar cane in Africa and from corn in small amounts in Asia. Biodiesel production is being considered from Jatropha (a drought resistant crop) that can be produced in most parts of Africa (Yamba and Matsika, 2004). It is estimated that with 10% ethanol-gasoline blending and 20% biodiesel-diesel blending in southern Africa, a reduction of 2.5 MtCO2 and 9.4 MtCO2 respectively per annum can be realized. Malaysian palm oil and US soybean oils are currently being used as biodiesel transport fuel in limited quantities and other oilseed crops are being considered elsewhere.

For the future, the conversion of ligno-cellulosic sources into biofuels is the most attractive biomass option. Ligno-cellulosic sources are grasses and woody material. These include crop residues, such as wheat and rice straw, and corn stalks and leaves, as well as dedicated energy crops. Cellulosic crops are attractive because they have much higher yields per hectare than sugar and starch crops, they may be grown in areas unsuitable for grains and other food/feed crops and thus do not compete with food, and the energy use is far less, resulting in much greater GHG reductions than with corn and most food crops (IEA, 2006a).

A few small experimental cellulosic conversion plants were being built in the USA in 2006 to convert crop residues (e.g., wheat straw) into ethanol, but considerably more R&D investment is needed to make these processes commercial.

These investments are beginning to be made. In 2006 BP announced it was committing 1 billion US$ to develop new biofuels, with special emphasis on bio-butanol, a liquid that can be easily blended with gasoline. Other large energy companies were also starting to invest substantial sums in biofuels R&D in 2006, along with the US Department of Energy, to increase plant yields, develop plants that are better matched with process conversion technologies and to improve the conversion processes. The energy companies in particular are seeking biofuels other than ethanol that would be more compatible with the existing petroleum distribution system.[22]

Biodiesel is less promising in terms of cost and production potential than cellulosic fuels but is receiving increasing attention. Bioesters are produced by a chemical reaction between vegetable or animal oil and alcohol, such as ethanol or methanol. Their properties are similar to those of diesel oil, allowing blending of bioesters with diesel or the use of 100% bioesters in diesel engines, and they are all called biodiesel. Blends of 20% biodiesel with 80% petroleum diesel (B20) can generally be used in unmodified diesel engines.[23]

Diesel fuel can also be produced through thermochemical hydrocracking of vegetable oil and animal fats. This technology has reached the demonstration stage. In Finland and Brazil[24] a commercial production project is under way. The advantage of the hydrocracked biodiesel is its stability and compatibility with conventional diesel (Koyama *et al*., 2006).

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20 http://www.eere.energy.gov/afdc/afv/eth_vehicles.html, http://en.wikipedia.org/wiki/Flexible-fuel_vehicle.
21 http://www.epa.gov/smartway/growandgo/documents/factsheet-e85.htm.
22 http://www.greencarcongress.com/2006/06/bp_and_dupont_t.html.
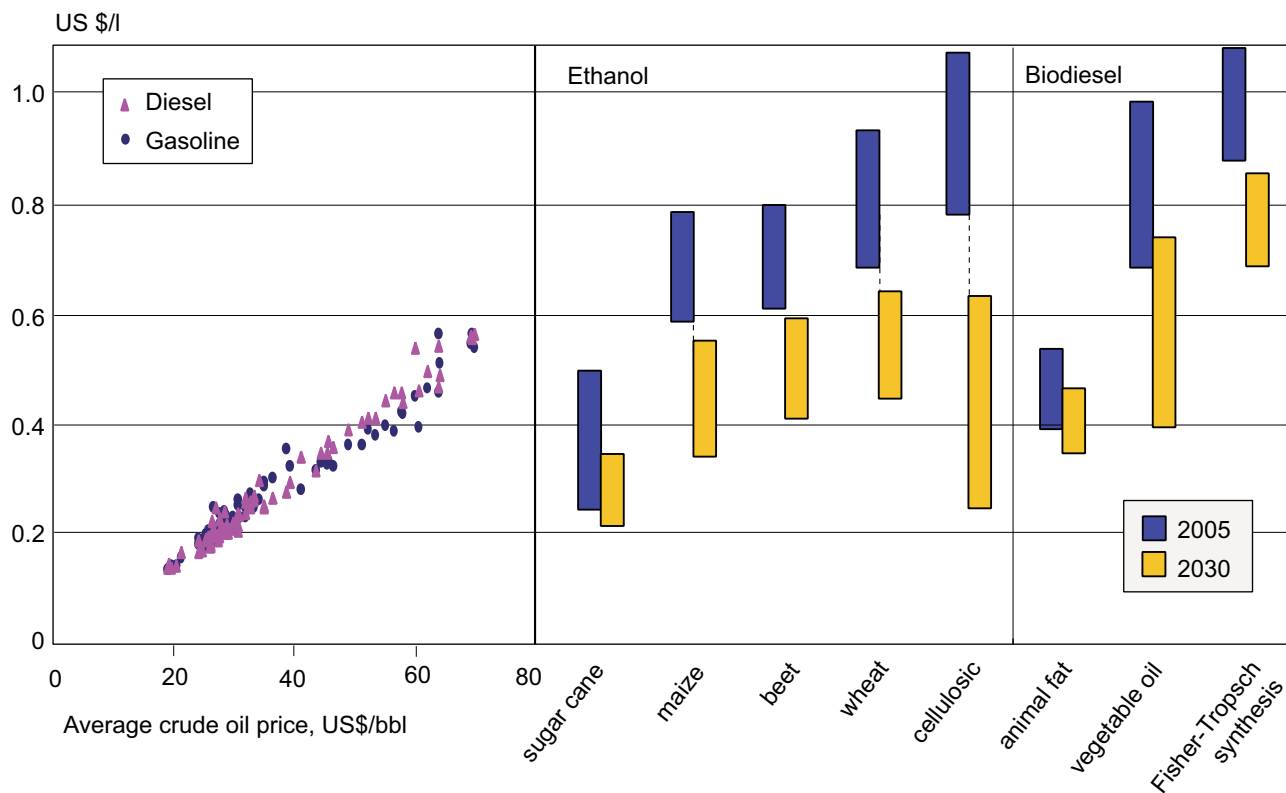23 http://www.eere.energy.gov/afdc/altfuel/biodiesel.html.

US $/l

Figure 5.9: *Comparison of cost for various biofuels with those for gasoline and diesel*
Source: IEA, 2006b.

A large drawback of biodiesel fuels is the very high cost of feedstocks. If waste oils are used the cost can be competitive, but the quantity of waste oils is miniscule compared to transport energy consumption. If crops are used, the feedstock costs are generally far higher than for sugar, starch or cellulosic materials. These costs are unlikely to drop since they are the same highly developed crops used for foods and food processing. Indeed, if diverted to energy use, the oil feedstock costs are likely to increase still further, creating a direct conflict with food production. The least expensive oil feedstock at present is palm oil. Research is ongoing into new ways of producing oils. The promising feedstock seems to be algae, but cost and scale issues are still uncertain.

For 2030 IEA (2006a) reports mitigation potentials for bioethanol between 500–1200 $MtCO_2$, with possibly up to 100–300 $MtCO_2$ of that for ligno-cellulosic ethanol (or some other bio-liquid). The long-term potential for ligno-cellulosic fuels beyond 2030 is even greater. For biodiesel, it reports mitigation potential between 100–300 $MtCO_2$.

The GHG reduction potential of biofuels, especially with cellulosic materials, is very large but uncertain. IEA estimated the total mitigation potential of biofuels in the transport sector in 2050 to range from 1800 to 2300 $MtCO_2$ at 25 US$/$tCO_2$-

eq. based on scenarios with a respective replacement of 13 and 25% of transport energy demand by biofuels (IEA, 2006a). The reduction uncertainty is huge because of uncertainties related to costs and GHG impacts.

Only in Brazil is biofuel competitive with oil at 50 US$ per barrel or less. All others cost more. As indicated in Figure 5.9, biofuel production costs are expected to drop considerably, especially with cellulosic feedstocks. But even if the processing costs are reduced, the scale issue is problematic. These facilities have large economies of scale. However, there are large diseconomies of scale in feedstock production (Sperling, 1985). The cost of transporting bulky feedstock materials to a central point increases exponentially, and it is difficult assembling large amount of contiguous land to serve single large processing facilities.

Another uncertainty is the well-to-wheel reduction in GHGs by these various biofuels. The calculations are very complex because of uncertainties in how to allocate GHG emissions across the various products likely to be produced in the bio-refinery facilities, how to handle the effects of alternative uses of land, and so on, and the large variations in how the crops are grown and harvested, as well as the uncertain efficiencies and design configurations of future process technologies and
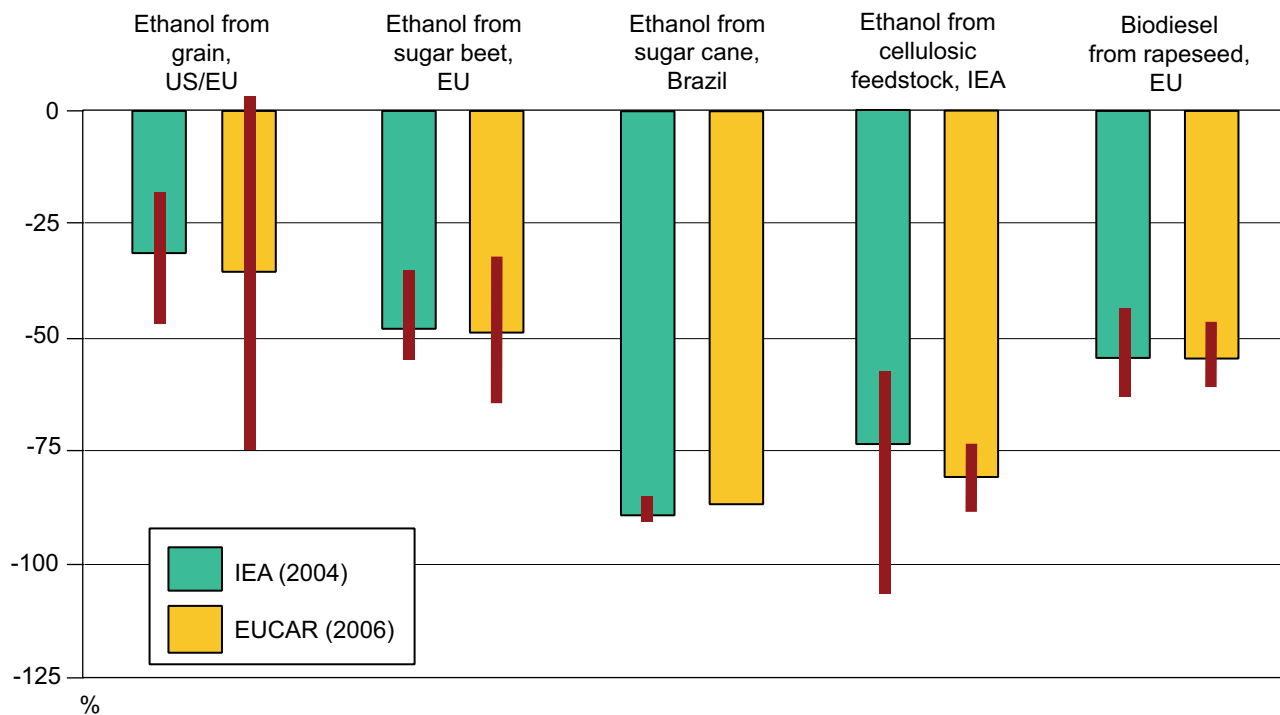
24 Brasil Energy, No.397-July/August (2006), 40:"H-Bio, The Clean Diesel".

Figure 5.10: *Reduction of well-to-wheels GHG emissions compared to conventionally fuelled vehicles*
Note: bars indicate range of estimates.
Source: IEA, 2004c; EUCAR/CONCAWE/JRC, 2006.

bio-engineering plant materials. Typical examples are shown in Figure 5.10.

Ethanol from sugar cane, as produced in Brazil, provides significant reductions in GHG emissions compared to gasoline and diesel fuel on a 'well-to-wheels' basis. These large reductions result from the relatively energy efficient nature of sugar cane production, the use of bagasse (the cellulosic stalks and leaves) as process energy and the highly advanced state of Brazilian sugar farming and processing. Ongoing research over the years has improved crop yields, farming practices and process technologies. In some facilities the bagasse is being used to cogenerate electricity which is sold back to the electricity grid.

In contrast, the GHG benefits of ethanol made from corn are minor (Ribeiro & Yones-Ibrahim, 2001). Lifecycle estimates range from a net loss to gains of about 30%, relative to gasoline made from conventional oil. Farrell *et al*. (2006) evaluates the many studies and concludes that on average the reductions are probably about 13% compared to gasoline from conventional oil. The corn-ethanol benefits are minimal because corn farming and processing are energy intensive.

Biofuels might play an important role in addressing GHG emissions in the transport sector, depending on their production pathway (Figure 5.10). In the years to come, some biofuels may become economically competitive, as the result of increased biomass yields, developments of plants that are better suited

to energy production, improved cellulosic conversion processes and even entirely new energy crops and conversion processes. In most cases, it will require entirely new businesses and industries. The example of ethanol in Brazil is a model. The question is the extent to which this model can be replicated elsewhere with other energy crops and production processes.

The biofuel potential is limited by:
- The amount of available agricultural land (and in case of competing uses for that land) for traditional and dedicated energy crops;
- The quantity of economically recoverable agricultural and silvicultural waste streams;
- The availability of proven and cost-effective conversion technology.

Another barrier to increasing the potential is that the production of biofuels on a massive scale may require deforestation and the release of soil carbon as mentioned in Chapter 8.4. Another important point on biofuels is a view from the cost-effectiveness among the sectors. When comparing the use of biofuel in the transport sector with its use in power stations, the latter is more favourable from a cost-effectiveness point of view (ECMT, 2007).

Natural Gas (CNG / LNG / GTL)
Natural gas, which is mainly methane (CH_4), can be used directly in vehicles or converted into more compact fuels. It may be stored in compressed (CNG) or liquefied (LNG) form

on the vehicle. Also, natural gas may be converted in large petrochemical plants into petroleum-like fuels (the process is known as GTL, or gas-to-liquid). The use of natural gas as a feedstock for hydrogen is described in the hydrogen section.

CNG and LNG combustion characteristics are appropriate for spark ignition engines. Their high octane rating, about 120, allows a higher compression ratio than is possible using gasoline, which can increase engine efficiency. This requires that the vehicle be dedicated to CNG or LNG, however. Many current vehicles using CNG are converted from gasoline vehicles or manufactured as bifuel vehicles, with two fuel tanks. Bifuel vehicles cannot take full advantage of CNG's high octane ratio.

CNG has been popular in polluted cities because of its good emission characteristics. However, in modern vehicles with exhaust gas after-treatment devices, the non-CO_2 emissions from gasoline engines are similar to CNG, and consequently CNG loses its emission advantages in term of local pollutants; however it produces less CO_2. Important constraints on its use are the need for a separate refuelling infrastructure system and higher vehicle costs – because CNG is stored under high pressure in larger and heavier fuel tanks.

Gas-to-liquids (GTL) processes can produce a range of liquid transport fuels using Fischer-Tropsch or other conversion technologies. The main GTL fuel produced will be synthetic sulphur-free diesel fuel, although other fuels can also be produced. GTL processes may be a major source of liquid fuels if conventional oil production cannot keep up with growing demand, but the current processes are relatively inefficient: 61–65% (EUCAR/CONCAWE/JRC, 2006) and would lead to increased GHG emissions unless the CO_2 generated is sequestered.

DME can be made from natural gas, but it can also be produced by gasifying biomass, coal or even waste. It can be stored in liquid form at 5–10 bar pressure at normal temperature. This pressure is considerably lower than that required to store natural gas on board vehicles (200 bar). A major advantage of DME is its high cetane rating, which means that self-ignition will be easier. The high cetane rating makes DME suitable for use in efficient diesel engines.

DME is still at the experimental stage and it is still too early to say whether it will be commercially viable. During experiments, DME has been shown to produce lower emissions of hydrocarbons, nitric oxides and carbon monoxide than diesel and zero emissions of soot (Kajitani *et al*., 2005). There is no current developed distribution network for DME, although it has similarities to LPG and can use a similar distribution system. DME has a potential to reduce GHG emissions since it

has a lower carbon intensity (15 tC/TJ) than petroleum products (18.9–20.2 tC/TJ) (IPCC, 1996).

Hydrogen / Fuel Cells

During the last decade, fuel cell vehicles (FCVs) have attracted growing attention and have made significant technological progress. Drivers for development of FCVs are global warming (FCVs fuelled by hydrogen have zero CO_2 emission and high efficiency), air quality (zero tailpipe emissions), and energy security (hydrogen will be produced from a wide range of sources), and the potential to provide new desirable customer attributes (low noise, new designs).

There are several types of FCVs; direct-drive and hybrid power train architectures fuelled by pure hydrogen, methanol and hydrocarbons (gasoline, naphtha). FCVs with liquid fuels have advantages in terms of fuel storage and infrastructure, but they need on-board fuel reformers (fuel processors), which leads to lower vehicle efficiency (30–50% loss), longer start-up time, slower response and higher cost. Because of these disadvantages and rapid progress on direct hydrogen systems, nearly all auto manufacturers are now focused on the pure hydrogen FCV. Significant technological progress has been made since TAR including: improved fuel cell durability, cold start (sub-freezing) operation, increased range of operation, and dramatically reduced costs (although FCV drive train costs remain at least an order of magnitude greater than internal combustion engine (ICE) drive train costs) (Murakami and Uchibori, 2006).

In addition, many demonstration projects have been initiated since TAR[25]. Since 2000, members of the California Fuel Cell Partnership have placed 87 light-duty FCVs and 5 FC buses in California, which have travelled over 590,000 km on California's roads and highways. In 2002–2003, Japanese automakers began leasing FCVs in Japan and the USA, now totalling 17 vehicles. In 2004, US DOE started government/industry partnership 'learning demonstrations' for testing, demonstrating and validating hydrogen fuel cell vehicles and infrastructure and vehicle/infrastructure interfaces for complete system solutions. In Europe, there are several partnerships for FCV demonstration such as CUTE (Clean Urban Transport for Europe), CEP (Clean Energy Partnership) and ECTOS (Ecological City Transport System), using more than 30 buses and 20 passenger cars.

The recent US (NRC/NAE, 2004) and EU (JRC/IPTS, 2004) analyses conclude:

Although the potential of FCVs for reducing GHG emissions is very high there are currently many barriers to be overcome before that potential can be realized in a commercial market. These are:

- To develop durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems and reduce the

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25 See the report of JHFC, Current status of overseas FCV demonstration, http://www.jhfc.jp/j/data/data/h17/11_h17seminar_e.pdf.
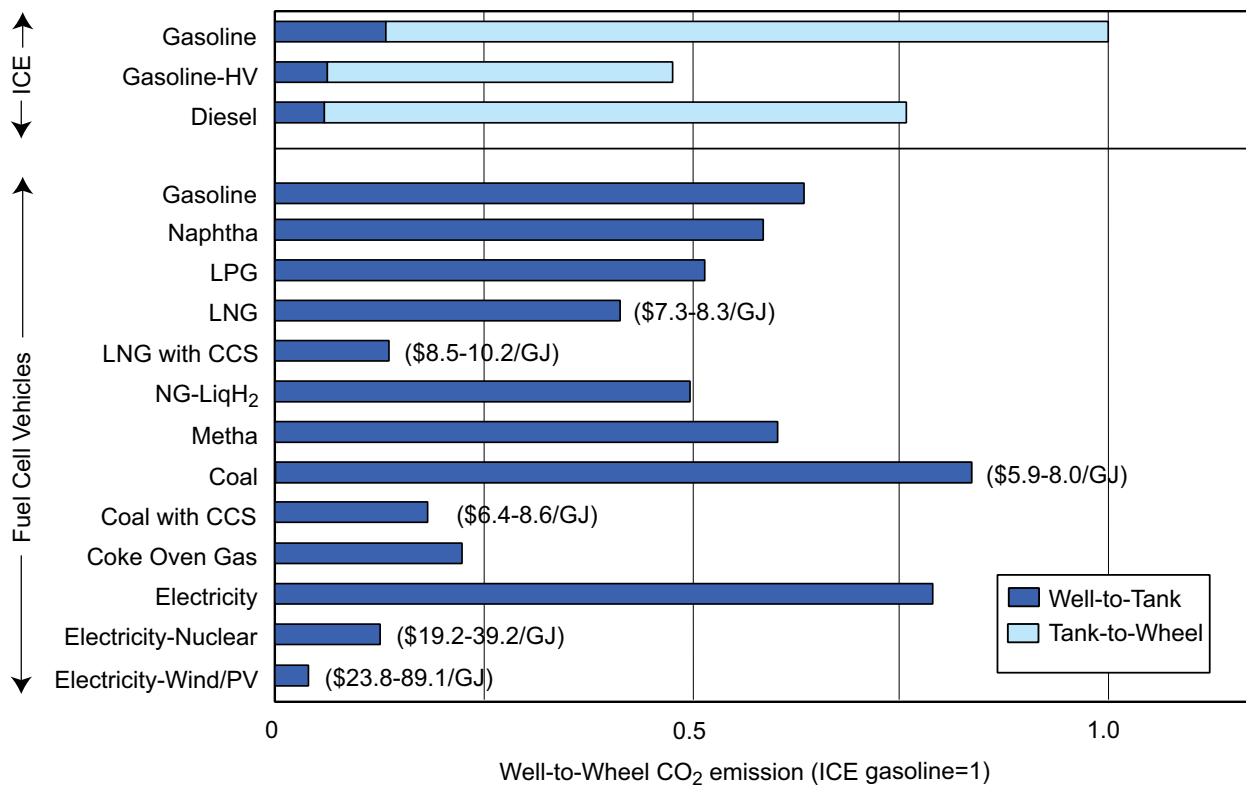
Figure 5.11: *Well-to-wheel CO$_2$ emission for major pathways of hydrogen with some estimates of hydrogen production cost (numbers in parentheses)*
Source: Toyota/Mizuho, 2004; NRC/NAE, 2004.

cost of fuel cell and storage components to be competitive with today's ICEs;

- To develop the infrastructure to provide hydrogen for the light-duty vehicle user;
- To sharply reduce the costs of hydrogen production from renewable energy sources over a time frame of decades. Or to capture and store ('sequester') the carbon dioxide byproduct of hydrogen production from fossil fuels.

Public acceptance must also be secured in order to create demand for this technology. The IEA echoes these points while also noting that deployment of large-scale hydrogen infrastructure at this point would be premature, as some of the key technical issues that are still being worked on, such as fuel cell operating conditions and hydrogen on-board storage options, may have a considerable impact on the choice of hydrogen production, distribution and refuelling (IEA, 2005).

The GHG impact of FCVs depends on the hydrogen production path and the technical efficiency achieved by vehicles and H$_2$ production technology. At the present technology level with FCV tank-to-wheel efficiency of about 50% and where hydrogen can be produced from natural gas at 60% efficiency, well-to-wheel (WTW) CO$_2$ emissions can be reduced by 50–60% compared to current conventional gasoline vehicles. In the future, those efficiencies will increase and the potential of WTW CO$_2$ reduction can be increased to nearly 70%. If hydrogen is derived from water by electrolysis using electricity produced

using renewable energy such as solar and wind, or nuclear energy, the entire system from fuel production to end-use in the vehicle has the potential to be a truly 'zero emissions'. The same is almost true for hydrogen derived from fossil sources where as much as 90% of the CO$_2$ produced during hydrogen manufacture is captured and stored (see Figure 5.11).

FCV costs are expected to be much higher than conventional ICE vehicles, at least in the years immediately following their introduction and H$_2$ costs may exceed gasoline costs. Costs for both the vehicles and fuel will almost certainly fall over time with larger-scale production and the effects of learning, but the long-term costs are highly uncertain. Figure 5.11 shows both well-to-wheels emissions estimates for several FCV pathways and their competing conventional pathways, as well as cost estimates for some of the hydrogen pathways.

Although fuel cells have been the primary focus of research on potential hydrogen use in the transport sector, some automakers envision hydrogen ICEs as a useful bridge technology for introducing hydrogen into the sector and have built prototype vehicles using hydrogen. Mazda has started to lease bi-fuel (hydrogen or gasoline) vehicles using rotary engines and BMW has also converted a 7-series sedan to bi-fuel operation using liquefied hydrogen (Kiesgen *et al*., 2006) and is going to lease them in 2007. Available research implies that a direct injected turbocharged hydrogen engine could potentially achieve efficiency greater than a DI diesel (Wimmer *et al*.,

2005), although research and development challenges remain, including advanced sealing technology to insure against leakage with high pressure injection.

Electric vehicles

Fuel cell and hybrid vehicles gain their energy from chemical fuels, converting them into electricity onboard. Pure electric vehicles operating today are either powered from off-board electricity delivered through a conductive contact – usually buses with overhead wires or trains with electrified 'third rails' – or by electricity acquired from the grid and stored on-board in batteries. Future all-electric vehicles might use inductive charging to acquire electricity, or use ultracapacitors or flywheels in combination with batteries to store electricity on board.

The electric vehicles are driven by electric motors with high efficiencies of more than 90%, but their short driving range and short battery life have limited the market penetration. Even a limited driving range of 300 km requires a large volume of batteries weighing more than 400 kg (JHFC, 2006). Although the potential of CO_2 reduction strongly depends on the power mix, well-to-wheels CO_2 emission can be reduced by more than 50% compared to conventional gasoline-ICE (JHFC, 2006).

Vehicle electrification requires a more powerful, sophisticated and reliable energy-storage component than lead-acid batteries. These storage components will be used to start the car and also operate powerful by-wire control systems, store regenerative braking energy and to operate the powerful motor drives needed for hybrid or electric vehicles. Nickel metal hydride (NiMH) batteries currently dominate the power-assist hybrid market and Li ion batteries dominate the portable battery business. Both are being aggressively developed for broader automotive applications. The energy density has been increased to 170 Wh kg^{-1} and 500 Wh L^{-1} for small-size commercial Li ion batteries (Sanyo, 2005) and 130 Wh kg^{-1} and 310 Wh L^{-1} for large-size EV batteries (Yuasa, 2000). While NiMH has been able to maintain hybrid vehicle high-volume business, Li ion batteries are starting to capture niche market applications (e.g., the idle-stop model of Toyota's Vitz). The major hurdle left for Li ion batteries is their high cost.

Ultracapacitors offer long life and high power but low energy density and high current cost. Prospects for cost reduction and energy enhancement and the possibility of coupling the capacitor with the battery are attracting the attention of energy storage developers and automotive power technologists alike. The energy density of ultracapacitors has increased to 15–20 Wh kg^{-1} (Power System, 2005), compared with 40–60 Wh kg^{-1} for Ni-MH batteries. The cost of these advanced capacitors is in the range of several 10s of dollars/Wh, about one order of magnitude higher than Li batteries.

5.3.1.4 Well-to-wheels analysis of technical mitigation options

Life cycle analysis (LCA) is the most systematic and comprehensive method for the assessment of the environmental impacts of transport technologies. However, non-availability, uncertainty or variability of data limit its application. One key difficulty is deciding where to draw the boundary for the analysis; another is treating the byproducts of fuel production systems and their GHG emission credits. Also in some cases, LCA data varies strongly across regions

For automobiles, the life-cycle chain can be divided into the fuel cycle (extraction of crude oil, fuel processing, fuel transport and fuel use during operation of vehicle) and vehicle cycle (material production, vehicle manufacturing and disposal at the end-of-life). For a typical internal combustion engine (ICE) vehicle, 70–90% of energy consumption and GHG emissions take place during the fuel cycle, depending on vehicle efficiency, driving mode and lifetime driving distance (Toyota, 2004).

Recent studies of the Well-to-wheels CO_2 emissions of conventional and alternative fuels and vehicle propulsion concepts include a GM/ANL (2005) analysis for North America, EU-CAR/CONCAWE/JRC (2006) for Europe and Toyota/Mizuho (2004) for Japan. Some results are shown in Fig. 5.12. Some of the differences, as apparent from Figure 5.12 for ICE-gasoline and ICE-D (diesel) reflect difference in the oil producing regions and regional differences in gasoline and diesel fuel requirements and processing equipment in refineries.

The Well-to-wheel CO_2 emissions shown in Fig. 5.12 are for three groups of vehicle/fuel combinations – ICE/fossil fuel, ICE/biofuel and FCV. The full well-to-wheels CO_2 emissions depend on not only the drive train efficiency (TTW: tank-to-wheel) but also the emissions during the fuel processing (WTT: well-to-tank). ICE-CNG (compressed natural gas) has 15–25% lower emissions than ICE-G (Gasoline) because natural gas is a lower-carbon fuel and ICE-D (Diesel) has 16–24% lower emissions due to the high efficiency of the diesel engine. The results for hybrids vary among the analyses due to different assumptions of vehicle efficiency and different driving cycles. Although Toyota's analysis is based on Prius, and using Japanese 10–15 driving cycle, the potential for CO_2 reduction is 20–30% in general.

Table 5.3 summarizes the results and provides an overview of implementation barriers. The lifecycle emissions of ICE vehicles using biofuels and fuel cell vehicles are extremely dependent on the fuel pathways. For ICE-Biofuel, the CO_2 reduction potential is very large (30–90%), though world potential is limited by high production costs for several biomass pathways and land availability. The GHG reduction potential for the natural gas-sourced hydrogen FCV is moderate, but lifecycle emissions can be dramatically reduced by using CCS
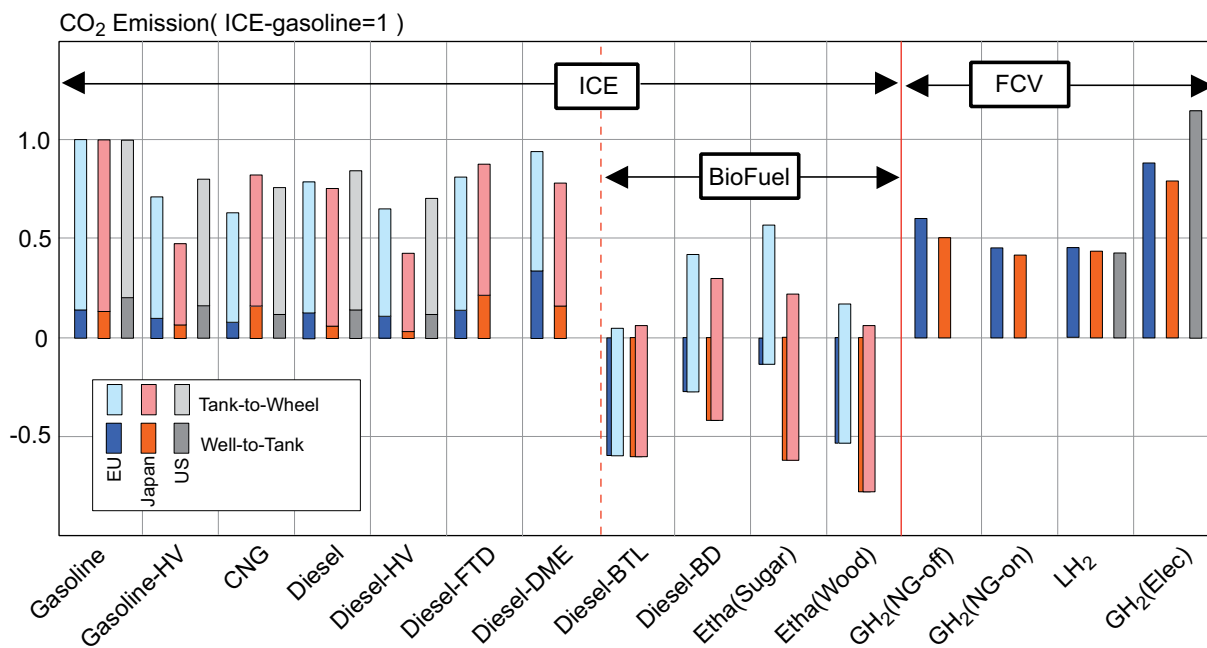
CO₂ Emission(ICE-gasoline=1)

Figure 5.12: *Comparison of three studies on Well-to-wheels CO₂ emission analyses*

Note: See text for an explanation of the legend. All the results are normalized by the value of ICE-G (gasoline).

Source: EUCAR/CONCAWE/JRC, 2006; GM/ANL, 2005; Toyota/Mizuho, 2004.

(carbon capture and storage) technology during H_2 production (FCEV-H2ccs in Table 5.3). Using renewable energy such as C-neutral biomass as a feedstock or clean electricity as an energy source (FCEV-RE-H_2) also will yield very low emissions.

5.3.1.5   Road transport: mode shifts

Personal motor vehicles consume much more energy and emit far more GHGs per passenger-km than other surface passenger modes. And the number of cars (and light trucks) continues to increase virtually everywhere in the world. Growth in GHG emissions can be reduced by restraining the growth in personal vehicle ownership. Such a strategy can, however, only be successful if high levels of mobility and accessibility can be provided by alternative means.

In general, collective modes of transport use less energy and generate less GHGs than private cars. Walking and biking emit even less. There is important worldwide mitigation potential if public and non-motorised transport trip share loss is reversed. The challenge is to improve public transport systems in order to preserve or augment the market share of low-emitting modes. If public transport gets more passengers, it is possible to increase the frequency of departures, which in turn may attract new passengers (Akerman and Hojer, 2006).

The USA is somewhat of an anomaly, though. In the USA, passenger travel by cars generates about the same GHG emissions as bus and air travel on a passenger-km basis (ORNL Transportation Energy Databook; ORNL, 2006). That is mostly because buses have low load factors in the USA. Thus, in the USA, a bus-based strategy or policy will not necessarily lower GHG emissions. Shifting passengers to bus is not simply a matter of filling empty seats. To attract more passengers, it is necessary to enhance transit service. That means more buses operating more frequently – which means more GHG emissions. It is even worse than that, because transit service is already offered where ridership[26] demand is greatest. Adding more service means targeting less dense corridors or adding more service on an existing route. There are good reasons to promote transit use in the USA, but energy use and GHGs are not among them.

Virtually everywhere else in the world, though, transit is used more intensively and therefore has a GHG advantage relative to cars. Table 5.4 shows the broad average GHG emissions from different vehicles and transport modes in a developing country context. GHG emissions per passenger-km are lowest for transit vehicles and two-wheelers. It also highlights the fact that combining alternative fuels with public transport modes can reduce emissions even further.

It is difficult to generalize, though, because of substantial differences across nations and regions. The types of buses, occupancy factors, and even topography and weather can affect emissions. For example, buses in India and China tend

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26 The number of passengers using a specific form of public transport.

Table 5.3: *Reduction of Well-to-wheels GHG emissions for various drive train/fuel combinations*

		Drive train/Fuel	GHG reduction (%)	Barriers
ICE	Fossil fuel	Gasoline (2010)	12-16	
		Diesel	16-24	Emissions (NO_x, PM)
		CNG	15-25	Infrastructure, storage
		G-HEV	20-52	Cost, battery
		D-HEV	29-57	Cost
	Biofuel	Ethanol-Cereal	30-65	Cost, availability (biomass, land), competition with food
		Ethanol-Sugar	79-87	
		Biodiesel	47-78	
		Advanced biofuel (cellulosic ethanol)	70-95	Technology, cost, environmental impact, competition with usage of other sectors
	H_2	H_2-ICE	6-16	H2 storage, cost
				Cost, infrastructure, deregulation
FCV		FCEV	43-59	
		FCEV+H_2ccs	78-86	Technology (stack, storage), cost, durability
		FCEV+RE-H_2	89-99	

Source: EUCAR/CONCAWE/JRC, 2006, GM/ANL, 2005 and Toyota/Mizuho (2004).

to be more fuel-efficient than those in the industrialized world, primarily because they have considerably smaller engines and lack air conditioning (Sperling and Salon, 2002).

Public transport

In addition to reducing transport emissions, public transport is considered favourably from a socially sustainable point of view because it gives higher mobility to people who do not have access to car. It is also attractive from an economically sustainable perspective since public transport provides more capacity at less marginal cost. It is less expensive to provide additional capacity by expanding bus service than building new roads or bridges. The expansion of public transport in the form of large capacity buses, light rail transit and metro or suburban rail can be feasible mitigation options for the transport sector.

The development of new rail services can be an effective measure for diverting car users to carbon-efficient mode while providing existing public transport users with upgraded service. However, a major hurdle is higher capital and possibly operating cost of the project. Rail is attractive and effective at generating high ridership in very dense cities. During the 1990s, less capital-intensive public transport projects such as light rail transit (LRT) were planned and constructed in Europe, North America and Japan. The LRT systems were successful in some regions, including a number of French cities where land use and transport planning is often well integrated (Hylen and Pharoah, 2002), but less so in other cities especially in the USA (Richmond, 2001; Mackett and Edwards, 1998), where more attention has been paid to this recently.

Around the world, the concept of bus rapid transit (BRT) is gaining much attention as a substitute for LRT and as an enhancement of conventional bus service. BRT is not new. Plans and studies for various BRT type alternatives have been prepared since the 1930s and a major BRT system was installed in Curitiba, Brazil in the 1970s (Levinson *et al*., 2002). But only since about 2000 has the successful Brazilian experience gained serious attention from cities elsewhere.

BRT is 'a mass transit system using exclusive right of way lanes that mimic the rapidity and performance of metro systems, but utilizes bus technology rather than rail vehicle technology' (Wright, 2004). BRT systems can be seen as enhanced bus service and an intermediate mode between conventional bus service and heavy rail systems. BRT includes features such as exclusive right of way lanes, rapid boarding and alighting, free transfers between routes and preboard fare collection and fare verification, as well as enclosed stations that are safe and comfortable, clear route maps, signage and real-time information displays, modal integration at stations and terminals, clean vehicle technologies and excellence in marketing and customer service. To be most effective, BRT systems (like other transport initiatives) should be part of a comprehensive strategy that includes increasing vehicle and fuel taxes, strict land-use controls, limits and higher fees on parking, and integrating transit systems into a broader package of mobility for all types of travellers (IEA, 2002b).

Most BRT systems today are being delivered in the range of 1–15 million US$/km, depending upon the capacity requirements and complexity of the project. By contrast, elevated rail systems and underground metro systems can cost from 50 million US$

Table 5.4: *GHG Emissions from vehicles and transport modes in developing countries*

	Load factor (average occupancy)	CO_2-eq emissions per passenger-km (full energy cycle)
Car (gasoline)	2.5	130-170
Car (diesel)	2.5	85-120
Car (natural gas)	2.5	100-135
Car (electric)[a]	2.0	30-100
Scooter (two-stroke)	1.5	60-90
Scooter (four-stroke)	1.5	40-60
Minibus (gasoline)	12.0	50-70
Minibus (diesel)	12.0	40-60
Bus (diesel)	40.0	20-30
Bus (natural gas)	40.0	25-35
Bus (hydrogen fuel cell)[b]	40.0	15-25
Rail Transit[c]	75% full	20-50

Note: All numbers in this table are estimates and approximations and are best treated as illustrative.

a) Ranges are due largely to varying mixes of carbon and non-carbon energy sources (ranging from about 20–80% coal), and also the assumption that the battery electric vehicle will tend to be somewhat smaller than conventional cars.
b) Hydrogen is assumed to be made from natural gas.
c) Assumes heavy urban rail technology ('Metro') powered by electricity generated from a mix of coal, natural gas and hydropower, with high passenger use (75% of seats filled on average).

Source: Sperling and Salon, 2002.

Table 5.5: *Cost and potential estimated for BRT in Bogota*

O & M[a] (%)	Fuel price per barrel (US$)	Cost (US$/t$CO_2$)
20	40	11.22
20	60	7.60
50	40	12.20
50	60	15.84

Note: Assuming 20% of the urban population uses the BRT each day.

a) Operation and maintenance (O & M) costs are expected to be high as the measure involves high demand for management and implementation beyond putting up the infrastructure.

Source: estimate based on Bogata CDM Project (footnote 27)

to over 200 million US$/km (Wright, 2004). BRT systems now operate in several cities throughout North America, Europe, Latin America, Australia, New Zealand and Asia. The largest and most successful systems to date are in Latin America in Bogotá, Curitiba and Mexico City (Karekezi *et al*., 2003).

Analysing the Bogotá Clean Development Mechanism project gives an insight into the cost and potential of implementing BRT in large cities. The CDM project shows the potential of moving about 20% of the city population per day on the BRT that mainly constitutes putting up dedicated bus lanes (130 km), articulated buses (1200) and 500 other large buses operating on feeder routes. The project is supported by an integrated fare system, centralized coordinated fleet control and improved bus management[27]. Using the investment costs, an assumed operation and maintenance of 20–50%[28] of investment costs per year, fuel costs of 40 to 60 US$ per barrel in 2030 and a discount rate of 4%, a BRT lifespan of 30 years, the cost of implementing BRT in the city of Bogotá was estimated to range from 7.6 US$/t$CO_2$ to 15.84 US$/t$CO_2$ depending on the price of fuel and operation and maintenance (Table 5.5). Comparing with results of Winkelman (2006), BRT cost estimates ranged from 14-66 US$/t$CO_2$ depending on the BRT package involved

(Table 5.6). The potential for CO_2 reduction for the city of Bogotá was determined to average 247,000 tCO_2 per annum or 7.4 million tCO_2 over a 30 year lifespan of the project.

Non-motorized transport (NMT)

The prospect for the reduction in CO_2 emissions by switching from cars to non-motorized transport (NMT) such as walking and cycling is dependent on local conditions. In the Netherlands, where 47% of trips are made by NMT, the NMT plays a substantial role up to distances of 7.5 km and walking up to 2.5 km (Rietveld, 2001). As more than 30% of trips made in cars in Europe cover distances of less than 3 km and 50% are less than 5 km (EC, 1999), NMT can possibly reduce car use in terms of trips and, to a lesser extent, in terms of kilometres. While the trend has been away from NMT, there is considerable potential to revive interest in NMT. In the Netherlands, with strong policies and cultural commitment, the modal share of bicycle and walking for accessing trains from home is about 35 to 40% and 25% respectively (Rietveld, 2001).

Walking and cycling are highly sensitive to the local built environment (ECMT, 2004a; Lee and Mouden, 2006). In Denmark, where the modal share of cycling is 18%, urban planners seek to enhance walking and cycling by shortening journey distances and providing better cycling infrastructure (Dill and Carr 2003, Page, 2005). In the UK where over 60% of people live within a 15 minute bicycle ride of a station, NMT could be increased by offering convenient, secure bicycle parking at stations and improved bicycle carriage on trains (ECMT, 2004a).

Safety is an important concern. NMT users have a much higher risk per trip of being involved in an accident than those using cars, especially in developing countries where most NMT users cannot afford to own a car (Mohan and Tiwari, 1999). Safety can be improved through traffic engineering and campaigns to educate drivers. An important co-benefit of NMT,

27 http://cdm.unfccc.int/Projects/DB/DNV-CUK1159192623.07/view.html.
28 O & M costs are expected to be high as the measure involves high demand for management and implementation beyond putting up the infrastructure.

gaining increasing attention in many countries, is public health (National Academies studies in the USA; Pucher, 2004).

In Bogotá, in 1998, 70% of the private car trips were under 3 km. This percentage is lower today thanks to the bike and pedestrian facilities. The design of streets was so hostile to bicycle travel that by 1998 bicycle trips accounted for less than 1% of total trips. After some 250 km of new bicycle facilities were constructed by 2001 ridership had increased to 4% of total trips. In most of Africa and in much of southern Asia, bicyclists and other non-motorised and animal traction vehicles are generally tolerated on the roadways by authorities. Non-motorised goods transport is often important for intermodal goods transport. A special form of rickshaw is used in Bangladesh, the bicycle van, which has basically the same design as a rickshaw (Hook, 2003).

Mitigation potential of modal shifts for passenger transport

Rapid motorization in the developing world is beginning to have a large effect on global GHG emissions. But motorization can evolve in quite different ways at very different rates. The amount of GHG emissions can be considerably reduced by offering strong public transport, integrating transit with efficient land use, enhancing walking and cycling, encouraging minicars and electric two-wheelers and providing incentives for efficient vehicles and low-GHG fuels. Few studies have analyzed the potential effect of multiple strategies in developing nations, partly because of a severe lack of reliable data and the very large differences in vehicle mix and travel patterns among varying areas.

Wright and Fulton (2005) estimated that a 5% increase in BRT mode share against a 1% mode share decrease of private automobiles, taxis and walking, plus a 2% share decrease of mini-buses can reduce CO_2 emissions by 4% at an estimated cost of 66 US$/$tCO_2$ in typical Latin American cities. A 5% or 4% increase in walking or cycling mode share in the same scenario analysis can also reduce CO_2 emissions by 7% or 4% at an estimated cost of 17 or 15 US$/$tCO_2$, respectively (Table 5.6). Although the assumptions of a single infrastructure unit cost and its constant impact on modal share in the analysis might be too simple, even shifting relatively small percentages of mode share to public transport or NMT can be worthwhile, because of a 1% reduction in mode share of private automobiles represents over 1 MtCO$_2$ through the 20-year project period.

Figure 5.13 shows the GHG transport emission results, normalized to year 2000 emissions, of four scenario analyses of developing nations and cities (Sperling and Salon, 2002). For three of the four cases, the 'high' scenarios are 'business-as-usual' scenarios assuming extrapolation of observable and emerging trends with an essentially passive government presence in transport policy. The exception is Shanghai, which is growing and changing so rapidly that 'business-as-usual' has little meaning. In this case the high scenario assumes both rapid

Table 5.6: *CO_2 reduction potential and cost per tCO_2 reduced using public transit policies in typical Latin American cities*

Transport measure	GHG reduction potential (%)	Cost per tCO$_2$ (US$)
BRT mode share increases from 0-5%	3.9	66
BRT mode share increases from 0-10%	8.6	59
Walking share increases from 20-25%	6.9	17
Bike share increases from 0-5%	3.9	15
Bike mode share increases from 1-10%	8.4	14
Package (BRT, pedestrian upgrades, cycleways)	25.1	30

Source: Wright and Fulton, 2005.

motorization and rapid population increases, with the execution of planned investments in highway infrastructure while at the same time efforts to shift to public transport falter (Zhou and Sperling, 2001).

5.3.1.6   *Improving driving practices (eco-driving)*

Fuel consumption of vehicles can be reduced through changes in driving practices. Fuel-efficient driving practices, with conventional combustion vehicles, include smoother deceleration and acceleration, keeping engine revolutions low, shutting off the engine when idling, reducing maximum speeds and maintaining proper tyre pressure (IEA, 2001). Results from studies conducted in Europe and the USA suggested possible improvement of 5–20% in fuel economy from eco-driving training. The mitigation costs of CO_2 by eco-driving training were mostly estimated to be negative (ECMT/IEA, 2005).

Eco-driving training can be attained with formal training programmes or on-board technology aids. It applies to drivers of all types of vehicles, from minicars to heavy-duty trucks. The major challenge is how to motivate drivers to participate in the programme, and how to make drivers maintain an efficient driving style long after participating (IEA, 2001). In the Netherlands, eco-driving training is provided as part of driving school curricula (ECMT/IEA, 2005).

5.3.2   Rail

Railway transport is widely used in many countries. In Europe and Japan, electricity is a major energy source for rail, while diesel is a major source in North America. Coal is also still used in some developing countries. Rail's main roles are high speed passenger transport between large (remote) cities, high density commuter transport in the city and freight transport over long distances. Railway transport competes with other transport modes, such as air, ship, trucks and private vehicles. Major
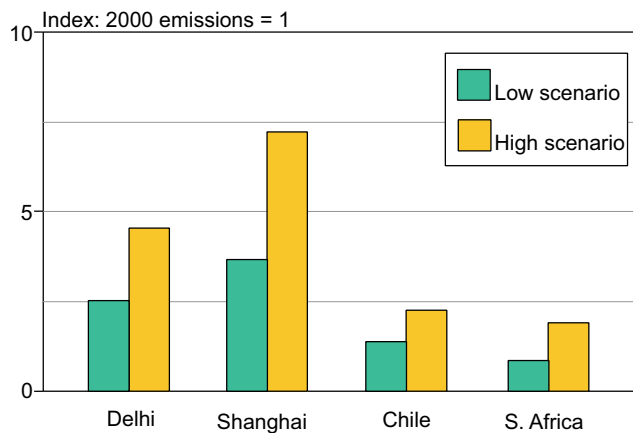
Index: 2000 emissions = 1

Figure 5.13: *Projections for transport GHG emissions in 2020 for some cities of developing countries*

Notes: Components of the Low 2020 scenario:

Delhi (Bose and Sperling, 2001): Completion of planned busways and rail transit, land-use planning for high density development around railway stations, network of dedicated bus lanes, promotion of bicycle use, including purchase subsidies and special lanes, promotion of car sharing, major push for more natural gas use in vehicles, economic re-straints on personal vehicles.

Shanghai (Zhou and Sperling, 2001): Emphasis on rapid rail system growth, high density development at railway sta-tions, bicycle promotion with new bike lanes and parking at transit stations, auto industry focus on minicars and farm cars rather than larger vehicles, incentives for use of high tech in minicars – electric, hybrid, fuel cell drive trains, promotion of car sharing.

Chile (O'Ryan et al., 2002): Overall focus on stronger use of market-based policy to insure that vehicle users pay the full costs of driving, internalizing costs of pollution and congestion, parking surcharges and restrictions, vehicle fees, and road usage fees, improvements in bus and rail systems, encourage-ment of minicars, with lenient usage and parking rules and strong commitment to alternative fuels, especially natural gas. By 2020, all taxis and 10% of other light and medium vehicles will use natural gas; all new buses will use hydrogen, improvements in bus and rail sys-tems.

South Africa (Prozzi et al., 2002): Land-use policies towards more efficient growth patterns, strong push to improve public transport, including use of bus-ways in dense corridors, provision of new and better buses, strong government oversight of the minibus jitney industry, incentives to moderate private car use, coal-based synfuels shifts to imported natural gas as a feedstock

Source: Sperling and Salon, 2002.

R&D goals for railway transport are higher speeds, improved comfort, cost reductions, better safety and better punctuality. Many energy efficiency technologies for railways are discussed in the web site of the International Union of Railways.[29] R&D programmes aimed at CO_2 reduction include:

Reducing aerodynamic resistance

For high speed trains such as the Japanese Shinkansen, French TGV and German ICE, aerodynamic resistance dominates vehicle loads. It is important to reduce this resistance to reduce energy consumption and CO_2 emissions. Aerodynamic resistance is determined by the shape of the train. Therefore, research has been carried out to find the optimum shape by using computer simulation and wind tunnel testing. The latest series 700 Shinkansen train has reduced aerodynamic resistance by 31% compared with the first generation Shinkansen.

Reducing train weight

Reduction of train weight is an effective way to reduce energy consumption and CO_2 emission. Aluminium car bodies, lightweight bogies and lighter propulsion equipments are proven weight reduction measures.

Regenerative braking

Regenerative brakes have been used in railways for three decades, but with limited applications. For current systems, the electric energy generated by braking is used through a catenary for powering other trains, reducing energy consumption and CO_2 emissions. However, regenerative braking energy cannot be effectively used when there is no train running near a braking train. Recently research in energy storage device onboard or trackside is progressing in several countries. Lithium ion batteries, ultracapacitors and flywheels are candidates for such energy storage devices.

Higher efficiency propulsion system

Recent research on rail propulsion has focused on superconducting on-board transformers and permanent magnet synchronous traction motors.

Apart from the above technologies mainly for electric trains, there are several promising technologies for diesel swichers, including common rail injection system and hybridization/on-board use of braking energy in diesel-electric vehicles (see the web site of the International Union of Railways),

5.3.3   Aviation

Fuel efficiency is a major consideration for aircraft operators as fuel currently represents around 20% of total operating costs for modern aircraft (2005 data, according to ICAO estimates[30] for the scheduled airlines of Contracting States). Both aircraft and engine manufacturers pursue technological developments to reduce fuel consumption to a practical minimum. There are no fuel efficiency certification standards for civil aviation. ICAO[31] has discussed the question of whether such a standard would be desirable, but has been unable to develop any form of parameter from the information available that correlates sufficiently well with the aircraft/engine performance and is therefore unable to define a fuel efficiency parameter that might be used for a standard at this time. 'Point' certification could drive manufacturers to comply with the regulatory requirement, possibly at the expense of fuel consumption for other operational conditions and missions. Market pressures therefore determine fuel efficiency and CO_2 emissions.

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29   Energy Efficiency Technologies for Railways: http://www.railway-energy.org/tfee/index.php.
30   ICAO Estimates for the scheduled airlines of Contracting States, 2005.
31   Doc. 9836, CAEP/6, 2004.

Box 5.3 Constraints on aviation technology development

Technology developments in civil aviation are brought to the marketplace only after rigorous airworthiness and safety testing. The engineering and safety standards that apply, along with exacting weight minimisation, reliability and maintainability requirements, impose constraints to technology development and diffusion that do not necessarily apply to the same degree for other transport modes. Some of these certification requirements for engines are as follows:

- Altitude relight to 30000ft – the engine must be capable of relighting under severe adverse conditions
- Engine starting capability between –50°C–+50°C
- Ice, hail and water ingestion
- Fan blade off test – blade to be contained and engine to run down to idle
- ETOPS (extended range operations) clearance – demonstrable engine reliability to allow single engine flight for up to 240 minutes for twin-engine aircraft

In addition, the need to comply with stringent engine emissions and aircraft noise standards, to offer products that allow aircraft to remain commercially viable for three decades or more and to meet the most stringent safety requirements impose significant costs for developments. Moreover, a level of engineering excellence beyond that demanded for other vehicles is the norm. It is under these exacting conditions that improvements are delivered thus affect the rate at which improvements can be offered.

Technology developments

Aviation's dependence on fossil fuels, likely to continue for the foreseeable future, drives a continuing trend of fuel efficiency improvement through aerodynamic improvements, weight reductions and engine fuel efficient developments. New technology is developed not only to be introduced into new engines, but also, where possible, to be incorporated into engines in current production. Fuel efficiency improvements also confer greater range capability and extend the operability of aircraft. Evolutionary developments of engine and airframe technology have resulted in a positive trend of fuel efficiency improvements since the passenger jet aircraft entered service, but more radical technologies are now being explored to continue this trend.

Engine developments

Engine developments require a balancing of the emissions produced to both satisfy operational need (fuel efficiency) and regulatory need (NO_x, CO, smoke and HC). This emissions performance balance must also reflect the need to deliver safety, reliability, cost and noise performance for the industry. Developments that reduce weight, reduce aerodynamic drag or improve the operation of the aircraft can offer all-round benefits. Emissions – and noise – regulatory compliance hinders the quest for improved fuel efficiency, and is often most difficult for those engines having the highest pressure ratios (PR). Higher PRs increase the temperature of the air used for combustion in the engine, exacerbating the NO_x emissions challenge. Increasing an engine's pressure ratio is one of the options engine manufacturers use to improve engine efficiency. Higher pressure ratios are likely to be a continuing trend in engine development, possibly requiring revolutionary NO_x control techniques to maintain compliance with NO_x certification standards.

A further consideration is the need to balance not only emissions trade-offs, but the inevitable trade-off between emissions and noise performance from the engine and aircraft. For example, the engine may be optimised for minimum NO_x emissions, at which design point the engine will burn more fuel than it might otherwise have done. A similar design compromise may reduce noise and such performance optimisation must be conducted against engine operability requirements described in Box 5.3.

Aircraft developments

Fuel efficiency improvements are available through improvements to the airframe, as well as the engine. Most modern civil jet aircraft have low-mounted swept wings and are powered by two or four turbofan engines mounted beneath the wings. Such subsonic aircraft are about 70% more fuel efficient per passenger-km than 40 years ago. The majority of this gain has been achieved through engine improvements and the remainder from airframe design improvements. A 20% improvement in fuel efficiency of individual aircraft types is projected by 2015 and a 40–50% improvement by 2050 relative to equivalent aircraft produced today (IPCC, 1999). The current aircraft configuration is highly evolved, but has scope for further improvement. Technological developments have to be demonstrated to offer proven benefits before they will be adopted in the aviation industry, and this coupled with the overriding safety requirements and a product lifetime that has 60% of aircraft in service at 30 years age (ICAO, 2003) results in slower change than might be seen in other transport forms.

For the near term, lightweight composite materials for the majority of the aircraft structure are beginning to appear and promise significant weight reductions and fuel burn benefits. The use of composites, for example in the Boeing 787 aircraft

Table 5.7: *Weight breakdown for four kerosene-fuelled configurations with the same payload and range*

Configuration	Empty weight (t)	Payload (t)	Fuel (t)	Max TOW (t)
Baseline	236	86	178 (100%)	500
BWB	207	86	137 (77%)	430
Laminar Flying Wing (LFW)	226	86	83 (47%)	395
LFW with UDF	219	86	72 (40%)	377

Source: GbD, 2001.

(that has yet to enter service), could reduce fuel consumption by 20% below that of the aircraft the B787 will replace[32]. Other developments, such as the use of winglets, the use of fuselage airflow control devices and weight reductions have been studied by aircraft manufacturers and can reduce fuel consumption by around 7%[33]. But these can have limited practical applicability – for example, the additional fuel burn imposed by the weight of winglets can negate any fuel efficiency advantage for short haul operations.

Longer term, some studies suggest that a new aircraft configuration might be necessary to realise a step change in aircraft fuel efficiency. Alternative aircraft concepts such as blended wing bodies or high aspect ratio/low sweep configuration aircraft designs might accomplish major fuel savings for some operations. The blended wing body (flying wing) is not a new concept and in theory holds the prospect of significant fuel burn reductions: estimates suggest 20–30% compared with an equivalent sized conventional aircraft carrying the same payload (GbD, 2001; Leifsson and Mason, 2005). The benefits of this tailless design result from the minimised skin friction drag, as the tail surfaces and some engine/fuselage integration can be eliminated. Its development for the future will depend on a viable market case and will incur significant design, development and production costs.

Laminar flow technology (reduced airframe drag through control of the boundary layer) is likely to provide additional aerodynamic efficiency potential for the airframe, especially for long-range aircraft. This technology extends the smooth boundary layer of undisturbed airflow over more of the aerodynamic structure, in some cases requiring artificial means to promote laminar flow beyond its natural extent by suction of the disturbed flow through the aerodynamic surface. Such systems have been the subject of research work in recent times, but are still far from a flightworthy application. Long-term technical and economic viability have yet to be proven, despite studies suggesting that fuel burn could be reduced by between 10 and 20% for suitable missions (Braslow, 1999).

In 2001 the Greener by Design (GbD) technology subgroup of the Royal Aeronautical Society considered a range of possible future technologies for the long-term development of the aviation industry and their possible environmental benefits (GbD, 2001). It offered a view of the fuel burn reduction benefits that some advanced concepts might offer. Concepts considered included alternative aircraft configurations such as the blended wing body and the laminar flying wing, and the use of an unducted fan (open rotor) power plant. The study concluded that these two aircraft concepts could offer significant fuel burn reduction potential compared with a conventional aircraft design carrying an equivalent payload. Other studies (Leifsson and Mason, 2005) have suggested similar results. Table 5.7 summarises, from the GbD results, the theoretical fuel savings of these future designs relative to a baseline conventional swept wing aircraft for a 12,500 km design range, with the percentage fuel burn requirements for the mission.

Further reduction in both NO_x and CO_2 emission could be achieved by advances in airframe and propulsion systems which reduce fuel burn. In propulsion, the open rotor offers significant reductions in fuel burn over the turbofan engines used typically on current passenger jets. However, aircraft speed is reduced below typical jet aircraft speeds as a consequence of propeller tip speed limits and therefore this technology may be more suitable for short- and medium-haul operations where speed may be less important. The global average flight length in 2005 was 1239 km (ICAO, 2006) and many flights are over shorter distances than this average. However, rotor noise from such devices would need to be controlled within acceptable (regulatory) limits.

In summary, airframe and engine technology developments, weight reduction through increased used of advanced structural composites, and drag reduction, particularly through the application of laminar flow control, hold the promise of further aviation fuel burn reductions over the long term. Such developments will only be accepted by the aviation industry should they offer an advantage over existing products and meet demanding safety and reliability criteria.

Alternative fuels for aviation

Kerosene is the primary fuel for civil aviation, but alternative fuels have been examined. These are summarised in Box 5.4.

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32 http://www.boeing.bom/commercial/787family/specs.
33 NASA, www.nasa.gov/centers/dryden/about/Organisations/Technology/Facts?

Box 5.4 Alternative fuels for aviation

The applicability of alternative and renewable fuels for civil aviation has been examined by many countries, for both the environmental benefit that might be produced and to address energy security issues. One study, The Potential for Renewable Energy Sources in Aviation (PRESAV, 2003) concluded that biodiesel, Fischer-Tropsch synthetic kerosene liquefied hydrogen (H_2) could be suitable for aviation application. Fuel cost would be an issue as in comparative terms, in 2003, conventional aviation kerosene cost 4.6 US$/GJ whereas the cost of biodiesel, FT kerosene and H_2 would be in the respective ranges of 33.5–52.6 US$, 8–31.7 US$, 21.5–53.8 US$/GJ. In the and elsewhere, synthetic kerosene production is being studied the engine company Pratt and Whitney noted in a presentation (Biddle, 2006) that synthetic kerosene could be 'economically viable when crude prices reach (up to) 59 US$/barrel'. However, any alternative fuel for commercial aircraft will need to be compatible with aviation kerosene (to obviate the need for tank and system flushing on re-fuelling) and meet a comprehensive performance and safety specification.

A potential non-carbon fuel is hydrogen and there have been several studies on its use in aviation. An EC study (Airbus, 2004) developed a conceptual basis for applicability, safety, and the full environmental compatibility for a transition from kerosene to hydrogen for aviation. The study concluded that conventional aircraft designs could be modified to accommodate the larger tank sizes necessary for hydrogen fuels. However, the increased drag due to the increased fuselage volume would increase the energy consumption of the aircraft by between 9% and 14%. The weight of the aircraft structure might increase by around 23% as a result, and the maximum take-off weight would vary between +4.4% to –14.8% dependent on aircraft size, configuration and mission. The hydrogen production process would produce CO_2 unless renewable energy was used and the lack of hydrogen production and delivery infrastructure would be a major obstacle. The primary environmental benefit from the use of hydrogen fuel would be the prevention of CO_2 emissions during aircraft operation. But hydrogen fuelled aircraft would produce around 2.6 times more water vapour than the use of kerosene and water vapour is a GHG. The earliest implementation of this technology was suggested as between 15–20 years, provided that research work was pursued at an appropriate level. The operating cost of hydrogen-powered aircraft remains unattractive under today's economic conditions.

The introduction of biofuels could mitigate some of aviation's carbon emissions, if biofuels can be developed to meet the demanding specifications of the aviation industry, although both the costs of such fuels and the emissions from their production process are uncertain at this time.

Aviation potential practices

The operational system for aviation is principally governed by air traffic management constraints. If aircraft were to operate for minimum fuel use (and CO_2 emissions), the following constraints would be modified: taxi-time would be minimized; aircraft would fly at their optimum cruising altitude (for load and mission distance); aircraft would fly minimum distance between departure and destination (i.e., great circle distances) but modified to take account of prevailing winds; no holding/ stacking would be applied.

Another type of operational system/mitigation potential is to consider the total climate impact of aviation. Such studies are in their infancy but were the subject of a major European project 'TRADE-OFF'. In this project different methods were devised to minimize the total radiative forcing impact of aviation; in practice this implies varying the cruise altitudes as O_3 formation, contrails (and presumably cirrus cloud enhancement) are all sensitive to this parameter. For example, Fichter *et al.* (2005) found in a parametric study that contrail coverage could be reduced by approximately 45% by flying the global fleet 6,000 feet lower, but at a fuel penalty of 6% compared with a base case. Williams *et al.* (2003) also found that regional contrail coverage was reduced by flying lower with a penalty on fuel usage. By flying lower, NO_x emissions tend to increase also, but the removal rate of NO_x is more efficient at lower altitudes: this, compounded with a lower radiative efficiency of O_3 at lower altitudes meant that flying lower could also imply lower O_3 forcing (Grewe *et al.*, 2002). Impacts on cirrus cloud enhancement cannot currently be modelled in the same way, since current estimates of aviation effects on cirrus are rudimentary and based upon statistical analyses of air traffic and satellite data of cloud coverage (Stordal *et al.*, 2005) rather than modelling. However, as Fichter *et al.* (2005) note, to a first order, one might expect aviation-induced cirrus cloud to scale with contrails. The overall 'trade-offs' are complex to analyse since CO_2 forcing is long lasting, being an integral over time. Moreover, the uncertainties on some aviation forcings (notably contrail and cirrus) are still high, such that the overall radiative forcing consequences of changing cruise altitudes need to be considered as a time-integrated scenario, which has not yet been done. However, if contrails prove to be worth avoiding, then such drastic action of reducing all aircraft cruising altitudes need not be done, as pointed out by Mannstein *et al.* (2005), since contrails can be easily avoided – in principle – by relatively small changes in flight level, due to the shallowness of ice supersaturation layers. However, this more finely tuned operational change would not necessarily apply to O_3 formation as the magnitude is a continuous process rather than the case of contrails that are either short-lived or persistent. Further intensive research of the impacts is required to determine whether such operational measures can be environmentally beneficial.

ATM (Air Traffic Management) environmental benefits

The goal of RVSM (Reduced Vertical Separation Minimum) is to reduce the vertical separation above flight level (FL) 290 from the current 610 m (2000 ft) minimum to 305 m (1000 ft) minimum. This will allow aircraft to safely fly more optimum profiles, gain fuel savings and increase airspace capacity. The process of safely changing this separation standard requires a study to assess the actual performance of airspace users under the current separation (610 m) and potential performance under the new standard (305 m). In 1988, the ICAO Review of General Concept of Separation Panel (RGCSP) completed this study and concluded that safe implementation of the 305 m separation standard was technically feasible.

A Eurocontrol study (Jelinek *et al*., 2002) tested the hypothesis that the implementation of RVSM would lead to reduced aviation emissions and fuel burn, since the use of RVSM offers the possibility to optimise flight profiles more readily than in the pre-existing ATC (Air Traffic Control) regime. RVSM introduces six additional flight levels between FL290 and FL410 for all States involved in the EUR RVSM programme. The study analysed the effect from three days of actual traffic just before implementation of RVSM in the European ATC region, with three traffic days immediately after implementation of RVSM. It concluded that a clear trend of increasing environmental benefit was shown. Total fuel burn, equating to CO_2 and H_2O emissions, was reduced by between 1.6–2.3% per year for airlines operating in the European RVSM area. This annual saving in fuel burn translates to around 310,000 tonnes annually, for the year 2003.

Lower flight speeds

Speed comes at a cost in terms of fuel burn, although modern jet aircraft are designed to fly at optimum speeds and altitudes to maximise the efficiencies of their design. Flying slower would be a possibility, but a different engine would be required in order to maximise the efficiencies from such operation. The propfan – this being a conventional gas turbine powering a highly efficient rotating propeller system, as an open rotor or unducted fan – is already an established technology and was developed during the late 1980s in response to a significant increase in fuel cost at the time. The scimitar shaped blades are designed to minimise aerodynamic problems associated with high blade speeds, although one problem created is the noise generated by such devices. The fuel efficiency gains from unducted fans, which essentially function as ultra high bypass ratio turbofans, are significant and require the adoption of lower aircraft speeds in order to minimise the helical mach number at the rotating blade tip. Typically the maximum cruise speed would be less than 400 miles per hour, compared with 550 mph[34] for conventional jet aircraft. In the event the aero acoustic problem associated with propfans could be overcome, such aircraft might be suitable for short-haul operations where

speed has less importance. But there would be the need to influence passenger choice: propeller driven aircraft are often perceived as old fashioned and dangerous and many passengers are reluctant to use such aircraft.

5.3.4 Shipping

In the past few years, the International Maritime Organization (IMO) has started research and discussions on the mitigation of GHG emissions by the shipping industry. The potential of technical measures to reduce CO_2 emissions was estimated at 5–30% in new ships and 4–20% in old ships. These reductions could be achieved by applying current energy-saving technologies vis-à-vis hydrodynamics (hull and propeller) and machinery on new and existing ships (Marintek, 2000).

The vast majority of marine propulsion and auxiliary plants onboard ocean-going ships are diesel engines. In terms of the maximum installed engine output of all civilian ships above 100 gross tonnes (GT), 96% of this energy is produced by diesel power. These engines typically have service lives of 30 years or more. It will therefore be a long time before technical measures can be implemented in the fleet on any significant scale. This implies that operational emission abatement measures on *existing* ships, such as speed reduction, load optimization, maintenance, fleet planning, etc., should play an important role if policy is to be effective before 2020.

Marintek (2000) estimates the short-term potential of operational measures at 1–40%. These CO_2 reductions could in particular be achieved by fleet optimization and routing and speed reduction. A general quantification of the potential is uncertain, because ship utilization varies across different segments of shipping and the operational aspects of shipping are not well defined.

The long-term reduction potential, assuming implementation of technical or operational measures, was estimated for the major fuel consuming segments[35] of the world fleet as specific case studies. The result of this analysis was that the estimated CO_2 emission reduction potential of the world fleet would be 17.6% in 2010 and 28.2% in 2020. Even though this potential is significant, it was noted that this would not be sufficient to compensate for the effects of projected fleet growth (Marintek, 2000). Speed reduction was found to offer the greatest potential for reduction, followed by implementation of new and improved technology. Speed reduction is probably only economically feasible if policy incentives, such as CO_2 trading or emissions charges are introduced.

A significant shift from a primarily diesel-only fleet to a fleet that uses alternative fuels and energy sources cannot be expected until 2020, as most of the promising alternative

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34 1 mph = 1.6 km/h
35 In fact four segments covering 80% of the fuel consumption were assessed: tank, bulk, container and general cargo ships.

techniques are not yet tested to an extent that they can compete with diesel engines (Eyring *et al.*, 2005b). Furthermore, the availability of alternative fuels is currently limited and time is needed to establish the infrastructure for alternative fuels. For these reasons, in the short term switching to alternative fuels provides a limited potential in general, but a significant potential for segments where a switch from diesel to natural gas is possible (Skjølsvik, 2005). Switching from diesel to natural gas has a 20% CO_2 reduction potential and is being pursued as a measure in Norway for inland ferries and offshore supply vessels operating on the Norwegian Continental Shelf. The main obstacle to the increased utilization of natural gas is the access to LNG (Liquefied Natural Gas) and the technology's level of costs compared to traditional ship solutions based on traditional fuel (Skjølsvik, 2005). A co-benefit of a switch from diesel to natural gas is that it also reduces emissions of SO_x and NO_x that contribute to local air pollution in the vicinity of ports.

For the long-term (2050), the economical CO_2 reduction potential might be large. One potential option is a combination of solar panels and sails. The use of large sails for super tankers is currently being tested in Germany and looks promising and may even be a cost-effective measure in the short term in case oil prices continue to soar. The use of large sails does not require fleet turnover but can be added to existing vessels (retrofit). The introduction of hydrogen-propelled ships and the use of fuel cell power at least for the auxiliary engines seem to be a possibility as well. For larger vessels capable and reliable fuel-cell-based ship propulsion systems are still a long way into the future, but might be possible in 2050 (Eyring *et al.*, 2005b). Altmann *et al.* (2004) concluded that fuel cells offer the potential for significant environmental improvements both in air quality and climate protection. Local pollutant emissions and GHG emissions can be eliminated almost entirely over the full life cycle using renewable primary energies. The direct use of natural gas in high temperature fuel cells employed in large ships and the use of natural gas derived hydrogen in fuel cells installed in small ships allows for a GHG emission reduction of 20–40%.

5.4   Mitigation potential

As discussed earlier, under 'business-as-usual' conditions with assumed adequate supplies of petroleum, GHG emissions from transport are expected to grow steadily during the next few decades, yielding about an 80% increase from 2002–2030 or 2.1% per year. This growth will not be evenly distributed; IEA projections of annual CO_2 growth rates for 2002–2030 range from 1.3% for the OECD nations to 3.6% for the developing countries. The potential for reducing this growth will vary widely across countries and regions, as will the appropriate policies and measures that can accomplish such reduction.

Analyses of the potential for reducing GHG emissions in the transport sector are largely limited to national or sub-national studies or to examinations of technologies at the vehicle level, for example well-to-wheel analyses of alternative fuels and drive trains for light-duty vehicles. The TAR presented the results of several studies for the years 2010 and 2020 (Table 3.16 of the TAR), with virtually all limited to single countries or to the EU or OECD. Many of these studies indicated that substantial reductions in transport GHG emissions could be achieved at negative or minimal costs, although these results generally used optimistic assumptions about future technology costs and/or did not consider trade-offs between vehicle efficiency and other (valued) vehicle characteristics. Studies undertaken since the TAR have tended to reach conclusions generally in agreement with these earlier studies, though recent studies have focused more on transitions to hydrogen used in fuel cell vehicles.

This section will discuss some available studies and provide estimates of GHG emissions reduction potential and costs/tonne of carbon emissions reduced for a limited set of mitigation measures. These estimates do not properly reflect the wide range of measures available, many of which would likely be undertaken primarily to achieve goals other than GHG reduction (or saving energy), for example to provide mobility to the poor, reduce air pollution and traffic reduce congestion. The estimates do not include:

- Measures to reduce shipping emissions;
- Changes in urban structure that would reduce travel demand and enhance the use of mass transit, walking and bicycling;
- Transport demand management measures, including parking 'cash out', road pricing, inner city entry charges, etc.

5.4.1   Available worldwide studies

Two recent studies – the International Energy Agency's *World Energy Outlook* (IEA, 2004a) and the World Business Council on Sustainable Development's *Mobility 2030* (WBCSD, 2004a) – examined worldwide mitigation potential but were limited in scope. The IEA study focused on a few relatively modest measures and the WBCSD examined the impact of specified technology penetrations on the road vehicle sector (the study sponsors are primarily oil companies and automobile manufacturers) without regard to either cost or the policies needed to achieve such results. In addition, IEA has developed a simple worldwide scenario for light-duty vehicles that also explores radical reductions in GHG emissions.

World Energy Outlook postulates an 'Alternative scenario' to their Reference scenario projection described earlier, in which vehicle fuel efficiency is improved, there are increased sales of alternative-fuel vehicles and the fuels themselves and demand side measures reduce transport demand and encourage a switch to alternative and less energy intensive transport modes. Some specific examples of technology changes and policy measures are:
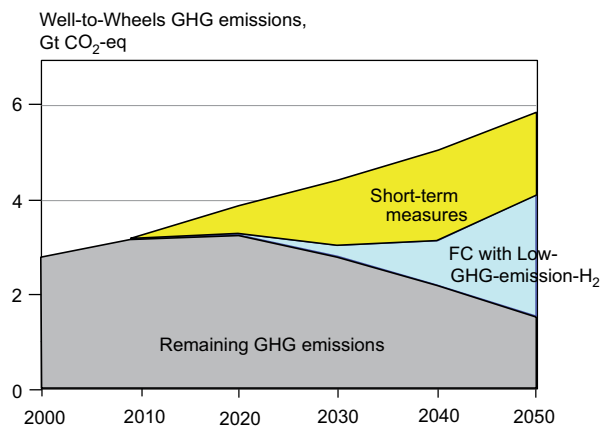
Well-to-Wheels GHG emissions,
Gt CO_2-eq

Figure 5.14: *Two possible scenarios for GHG reductions in Light-duty vehicles*
Source: IEA, 2004b.

- In the United States and Canada, vehicle fuel efficiency is nearly 20% better in 2030 than in the Reference scenario and hybrid and fuel-cell powered vehicles make up 15% of the stock of light-duty vehicles in 2030;
- Average fuel efficiency in the developing countries and transition economies are 10–15% higher than in the Reference scenarios;
- Measures to slow traffic growth and move to more efficient modes reduce road traffic by 5% in the European Union and 6% in Japan. Similarly, road freight is reduced by 8% in the EU and 10% in Japan.

The net reductions in transport energy consumption and CO_2 emissions in 2030 are 315 Mtoe, or 9.6% and 997 MtC, or 11.4%, respectively compared to the Reference scenario. This represents a 2002–2030 reduction in the annual growth rate of energy consumption from 2.1-1.3% per year, a significant accomplishment but one which still allows transport energy to grow by 57% during the period. CO_2 emissions grow a bit less because of the shift to fuels with less carbon intensity, primarily natural gas and biofuels.

IEA has also produced a technology brief that examines a simple scenario for reducing world GHG emissions from the transport sector (IEA, 2004b). The scenario includes a range of short-term actions, coupled with the development and deployment of fuel-cell vehicles and a low-carbon hydrogen fuel infrastructure. For the long-term actions, deployment of fuel-cell vehicles would aim for a 10% share of light-duty vehicle sales by 2030 and 100% by 2050, with a 75% per-vehicle reduction in GHG emissions by 2050 compared to gasoline vehicles. The short-term measures for light-duty vehicles are:
- Improvements in fuel economy of gasoline and diesel vehicles, ranging from 15% (in comparison to the IEA reference case) by 2020 to 35% by 2050;
- Growing penetration of hybrid vehicles, to 50% of sales by 2040;
- Widespread introduction of biofuels, with 50% lower well-

to-wheels GHG emissions per km than gasoline, with a 25% penetration by 2050;
- Reduced travel demand, compared to the reference case, of 20% by 2050.

Figure 5.14 shows the light-duty vehicle GHG emissions results of the scenario. The penetration of fuel cell vehicles by itself brings emissions back to their 2000-levels by 2050. Coupled with the nearer-term measures, GHG emissions peak in 2020 and retreat to half of their 2000-level by 2050.

The Mobility 2030 study examined a scenario postulating very large increases in the penetration of fuel efficient technologies into road vehicles, coupled with improvements in vehicle use, assuming different time frames for industrialized and developing nations.

The technologies and their fuel consumption and carbon emissions savings referenced to current gasoline ICEs were:

Technology	Carbon reduced/vehicle (%)
1. Diesels	18
2. Hybridization	30 (36 for diesel hybrids)
3. Biofuels	20-80
4. Fuel cells with fossil hydrogen	45
5. Carbon-neutral hydrogen	100

Figure 5.15 shows the effect of a scenario postulating the market penetration of all of the technologies as well as an assumed change in consumer preferences for larger vehicles and improved traffic flows. The scenario assumes that diesels make up 45% of light-duty vehicles and medium trucks by 2030; that half of all sales in these vehicle classes are hybrids, also by 2030; that one-third of all motor vehicle liquid fuels are biofuels (mostly advanced) by 2050; that half of LDV and medium truck vehicle sales are fuel cells by 2050, with the hydrogen beginning as fossil-based but gradually moving to 80% carbon neutral by 2050; that better traffic flow and other efficiency measures reduce GHG emissions by 10%; and that the underlying efficiency of light-duty vehicles improves by 0.6% per year due to steady improvements (e.g., better aerodynamics and tyres) and to reduced consumer preference for size and power. In this scenario, GHG emissions return to their 2000-level by 2050.

Mobility 2030's authors make it quite clear that for this 'mixed' scenario to be even remotely possible will require overcoming many major obstacles. The introduction and widespread use of hydrogen fuel cell vehicles for example requires huge reductions in the costs of fuel cells; breakthroughs in on-board hydrogen storage; major advances in hydrogen production; overcoming the built-in advantages of the current gasoline and diesel fuel infrastructure; demonstration and commercialization of carbon
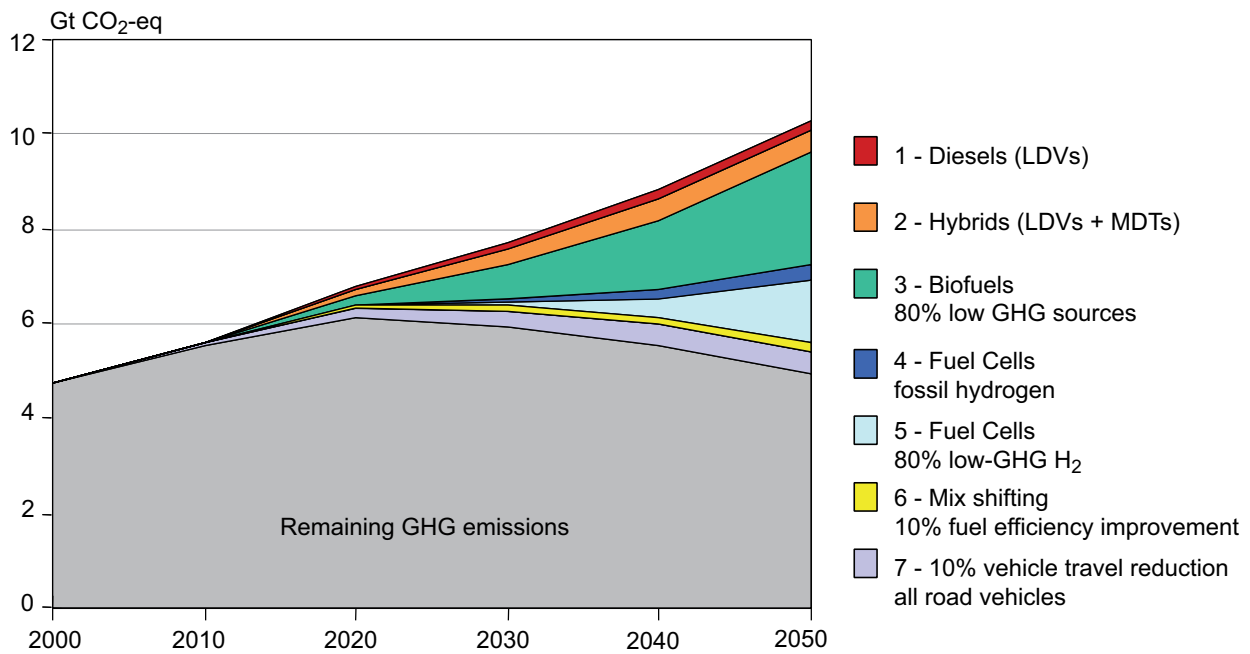
Figure 5.15: *The effect of a scenario postulating the market penetration of all technologies*
Source: WBCSD, 2004a.

sequestration technologies for fossil fuel hydrogen production (at least if GHG emission goals are to be reached); and a host of other R&D, engineering and policy successes.

Table 5.8 summarizes technical potentials for various mitigation options for the transport sector. As mentioned above, there are few studies dealing with worldwide analysis. In most of these studies, potentials are evaluated based on top-down scenario analysis. For combinations of specific power train technologies and fuels, well-to-wheels analyses are used to examine the various supply pathways. Technical potentials for operating practices, policies and behaviours are more difficult to isolate from economic and market potential and are usually derived from case studies or modelling analyses. Uncertainty is a key factor at all stages of assessment, from technology performance and cost to market acceptance.

5.4.2   Estimate of world mitigation costs and potentials in 2030

By extrapolating from recent analyses from the IEA and others an estimate can be given of the cost and potential for reducing transport CO_2 emissions. This section covers improving the efficiency of light-duty vehicles and aircraft, and the substitution of conventional fossil fuels by biofuels throughout the transport sector (though primarily in road vehicles). As noted above, these estimates do not represent the full range of options available to reduce GHG emissions in the transport sector.

5.4.2.1   Light-duty Vehicles

The following estimate of the overall GHG emissions reduction potential and costs for improving the efficiency of the world's light-duty vehicle fleet (thus reducing carbon emissions), is based on the IEA Reference Case, as documented in a spreadsheet model developed by the IEA for the Mobility 2030 project (WBSCD, 2004b). The cost estimates for total mitigation potential are provided in terms of 'societal' costs of reductions in GHG emissions, measured in US$/tonne of carbon (tC) or carbon dioxide (CO_2); the costs are the net of higher vehicle costs minus discounted lifetime fuel savings. Fuel savings benefits are measured in terms of the untaxed cost of the fuels at the retail level, and future savings are discounted at a low societal rate of 4% per year. These costs are not the same as those that would be faced by consumers, who would face the full taxed costs of fuel, would almost certainly use a higher discount rate, and might value only a few years of fuel savings. Also, they do not include the consumer costs of forgoing further increases in vehicle performance and weight. Over the past few decades, increasing acceleration performance and vehicle weight have stifled increases in fuel economy for light-duty vehicles and these trends must be stopped if substantial progress is to be made in fleet efficiency. Because consumers value factors such as vehicle performance, stopping these trends will have a perceived cost – but there is little information about its magnitude.

The potential improvements in light-duty fuel economy assumed in the analysis, and the costs of these improvements, are based on the scenarios in the MIT study summarised in Box 5.5. The efficiency improvements as mentioned in this study are

Table 5.8: *Summary table of CO_2 mitigation potentials in transport sector taken from several studies*

Study	Mitigation measure/policy	Region	CO_2 reduction (%)				CO_2 reduction (Mt)			
			2010	2020	2030	2050	2010	2020	2030	2050
IEA 2004a	Alternative scenario	World OECD Developing countries Transition economies	2.2 2 2.8 2.3	6.8 6.9 6.8 6.2	11.4 11.5 11.4 11.2		133 77 49 8	505 308 170 27	997 557 381 59	
IEA 2001	Improving Tech for Fuel Economy Diesel	OECD		30	40 5-15					
IEA 2002a	All scenarios included All scenarios included All scenarios included	NA Western Europe Japan	6.6 6.6 8.3	14.4 15.6 16.1			148 76 28	358 209 61		
IEA 2004d	Improving fuel economy Biofuels FCV with hydrogen refuelling COMBINING THESE THREE	World			18 12 7 30					
IEA 2004b	Reduction in fuel use per km Blend of biofuels Reduction in growth of LDV travel using hydrogen in vehicle	World		15 5 5 0	25 8 10 3	35 13 20 75				
ACEEE 2001	A-scenario B-scenario C-scenario	USA	9.9 11.8 13.2	26.3 30.6 33.4			132 158 176	418 488 532		
MIT 2004	Baseline Medium HEV Composite Combined policies	USA	 3-6	3.4 5.2 14.9 14-24	(2035) 16.8 29.9 44.4 32-50					

Greene and Schafer 2003	Efficiency standards
	  Light-duty vehicles
	  Heavy trucks
	  Commercial aircraft
	
	Replacement & alternative fuels
	  Low-carbon replacement fuels
	  Hydrogen fuel (all LDV fuel)
	
	Pricing policies
	  Low-carbon fuel subsidy
	  Carbon pricing
	  Variabilization
	
	Behavioural
	  Land use & infrastructure
	  System efficiency
	  Climate change education
	  Fuel economy information
	
	Total
		USA		(2015)
				6
				2
				1
				
				2
				1
				
				2
				3
				6
				
				3
				0
				1
				1
				
				22
					18
					3
					2
					
					7
					4
					
					6
					6
					9
					
					5
					1
					2
					1
					
					48					

WEC 2004	New technologies	World		30		46				
WBCSD 2004b	Road transport Diesels (LDVs) Hybrids (LDVs and MDTs) Biofuels-80% low GHG sources Fuel Cells-fossil hydrogen Fuel Cells-80% low-GHG hydrogen Mix shifting 10% FE improvement 10% Vehicle travel reduction-all vehicles	World		 0.9 2.4 5.7 5.9 5.9 6.7 9.4	 2.1 6.1 15.6 16.7 17.2 18.8 22.8	 1.8 6.1 29.5 32.7 45.3 47.3 51.9		 61 161 386 400 400 451 639	 160 474 1207 1293 1333 1455 1765	 181 623 3030 3364 4650 4864 5335

Box 5.5 Fuel economy benefits of multiple efficiency technologies

Several studies have examined the fuel economy benefits of simultaneously applying multiple efficiency technologies to light-duty vehicles. However, most of these are difficult to compare because they examine various types of vehicles, on different driving cycles, using different technology assumptions, for different time frames. The Massachusetts Institute of Technology has developed such an assessment for 2020 (MIT, 2000) with documentation of basic assumptions though with few details about the specific technologies that achieve these values, for a medium size passenger car driving over the official US Environmental Protection Agency driving cycle (Heywood et al., 2003). There are two levels of technology improvement – 'baseline' and 'advanced,' with the latter level of improvement further subdivided into conventional and hybrid drive trains.

Some of the key features of the 2020 vehicles are:
- Vehicle mass is reduced by 15% (baseline) and 22% (advanced) by a combination of greater use of high strength steel, aluminium and plastics coupled with advanced design;
- Tyre rolling resistance coefficient is reduced from the current .009 to .008 (baseline) and .006 (advanced);
- Drag coefficient is reduced to 0.27 (baseline) and 0.22 (advanced). The baseline level is at the level of the best current vehicles, while the advanced level should be readily obtainable for the best vehicles in 2020, but seems quite ambitious for a fleet average;
- Indicated engine efficiency increases to 41% in both baseline and advanced versions. This level of efficiency would likely require direct injection, full valve control (and possibly camless valves) and advanced engine combustion strategies.

The combined effects of applying this full range of technologies are quite dramatic (Table 5.9). From current test values of 30.6 mpg (7.69 litres/100 km) as a 2001 reference, baseline 2020 gasoline vehicles obtain 43.2 mpg (5.44 L/100 km), advanced gasoline vehicles 49.2 mpg (4.78 L/100 km) and gasoline hybrids 70.7 mpg (3.33 L/100 km); advanced diesels obtain 58.1 mpg (4.05 L/100 km) and diesel hybrids 82.5 mpg (2.85 L/100 km) (note that on-road values will be *at least* 15% lower). In comparison, Ricardo Consulting Engineers (Owen and Gordon, 2002) estimate the potential for achieving 92 g/km CO_2 emissions, equivalent to 68.6 mpg (3.43 L/100 km), for an advanced diesel hybrid medium size car 'without' substantive non-drive train improvements. This is probably a bit more optimistic than the MIT analysis when accounting for the additional effects of reduced vehicle mass, tyre rolling resistance and aerodynamic drag coefficient.

These values should be placed in context. First, the advanced vehicles represent 'leading edge' vehicles which must then be introduced more widely into the new vehicle fleet over a number of years and may take several years (if ever) to represent an 'average' vehicle. Second, the estimated fuel economy values are attainable only if trends towards ever-increasing vehicle performance are stifled; this may be difficult to achieve.

discounted somewhat to take into account the period in which the full benefits can be achieved. Further, fleet penetration of the technology advances are assumed to be delayed by 5 years in developing nations; however, because developing nation fleets are growing rapidly, higher efficiency vehicles, once introduced, may become a large fraction of the total fleet in these nations within a relatively short time. The technology assumptions for two 'efficiency scenarios' are as follows (Table 5.9a).

The high efficiency and medium efficiency scenarios achieve the following improvements in efficiency for the new light-duty vehicle fleet (Table 5.9b):

Table 5.10 shows the light-duty vehicle fuel consumption and (vehicle only) CO_2 emissions for the Reference scenario and the High and medium efficiency scenarios. In the Reference case, LDV fuel consumption increases by nearly 60% by 2030; the High Efficiency Case cuts this increase to 26% and the Medium efficiency scenario cuts it to 42%. For the OECD nations, the Reference Case projects only a 22% increase by 2030, primarily

because of moderate growth in travel demand, with the High efficiency scenario actually reducing fuel consumption in this group of nations by 9% and the Medium efficiency scenario reducing growth to only 6%. This regional decrease (or modest increase) in fuel use is overwhelmed by the rapid growth in the world's total fleet size and overall travel demand and the slower uptake of efficiency technologies in the developing nations. Because no change in the use of biofuels was assumed in this analysis, the CO_2 emissions in the scenarios essentially track the energy consumption paths discussed above. Figure 5.16 shows the GHG emissions path for the three scenarios, resulting in a mitigation potential of about 800 (High) and 400 (Medium) $MtCO_2$ in 2030.

Table 5.11 shows the cost of the reductions in GHG emissions in US$/t$CO_2$ for those reductions obtained by the 2030 new vehicle fleet over its lifetime, assuming oil prices of 30 US$, 40 US$, 50 US$ and 60 US$/bbl over the vehicles' lifetime.[36] Note that the costs in Table 5.11 do not apply to the carbon reductions achieved in that year by the entire LDV fleet (from Table

Table 5.9a: *Fuel economy and cost assumptions for cost and potentials analysis*

Medium size car	MPG (L/100 km)	Incr from Ref (%)	Cost (%)	∆Cost (US$)[a]
2001 reference	30.6 (7.69)	0	100	0
2030 baseline	43.2 (5.55)	41	105	1,000
2030 advanced	49.2 (4.78)	61	113	2,600
2030 hybrid	70.7 (3.33)	131	123	4,600
2030 diesel	58.1 (4.05)	90	119	3,800
2030 diesel hybrid	82.5 (2.85)	170	128	5,600

a) Cost differential based on a reference 20,000 US$ vehicle. See Box 5.5 for the definitions of the vehicle types.

Source: adapted from MIT (2000), as explained in the text.

Table 5.9b: *Efficiency improvements new light-duty vehicle fleet*

Region	% improvement from 2001 levels, high/medium			
	2015	2020	2025	2030
North America	**30/15**	**45/25**	**70/32**	**80/40**
Europe	30/25	40/30	55/35	70/40
Emerging Asia/Pacific	30/25	40/30	65/35	75/40
Rest of world	0/12+	30/20+	45/25+	60/30+

5.10), because those reductions are associated with successive waves of high efficiency vehicles entering the fleet during the approximately 15 year period before (and including) 2030.

The Table 5.11 results show that the 'social cost of carbon reduction' for light-duty vehicles varies dramatically across regions and with fuel prices (since the cost is the *net* of technology costs minus the value of fuel savings). The results are also quite different for the High and Medium efficiency scenarios, primarily because the estimated technology costs begin to rise more steeply at higher efficiency levels, raising the average cost/tonne of CO_2 in the High efficiency scenario. For the High efficiency scenario, CO_2 reduction costs are very high for the OECD countries aside from North America, even at 60 US$/bbl oil prices, reflecting the ambitious (and expensive) increases in that scenario, the relatively high efficiencies of those regions' fleets in the Reference Case, and the relatively low km/vehicle/year driven outside North America; on the other hand, the costs of the moderate increases in the Medium efficiency scenario are low to negative for all regions, reflecting the availability of moderate cost technologies capable of raising average vehicle efficiencies up to 30–40% or so.

The values in Table 5.11 are sensitive to several important assumptions:
- Technology costs: the costs assumed here appear to be considerably higher than those assumed in WEO 2006 (IEA, 2006a).

- Discount rates: the analysis assumes a low social discount rate of 4% in keeping with the purpose of the analysis. As noted, vehicle purchasers would undoubtedly use higher rates and would value fuel savings at retail fuel prices rather than the untaxed values used here; they might also only value a few years of fuel savings rather than the lifetime savings assumed here. WEO 2006 on the other hand, used a zero discount rate, substantially reducing the net cost of carbon reduction.
- Vehicle km travelled (vkt): this analysis used the IEA/WBCSD spreadsheet's assumption of constant vkt over time and applied these values to new cars. Actual driving patterns will depend on the balance of increasing road infrastructure and rapidly increasing fleet size in developing nations. Unless infrastructure keeps pace with growing fleet size, which will be difficult, the assumption of constant vkt/vehicle may prove accurate or even optimistic.
- Efficiency gains assumed in the Reference scenario: the Reference scenario assumed significant gains in most areas (aside from North America), which makes the Efficiency scenarios more expensive.

Table 5.12 shows the economic potential for reducing CO_2 emissions in the 2030 fleet of new LDVs as a function of world oil price.[37] The values show that much of the economic potential is available at a net savings, 'if consumer preference for power and other efficiency-robbing vehicle attributes is ignored'. Even at 30 US$/bbl oil prices, over half of the total

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36 Note, however, that these results do not take into account changes in travel demand that would occur with changing fuel price and changes in Reference case vehicle efficiency levels. At higher oil prices, the Reference case would likely have less travel and higher vehicle efficiency; this would, in turn, reduce the oil savings and GHG reductions obtained by the Efficiency case and would likely raise the costs/tonne C from the values shown here.

Table 5.10: *Regional and worldwide Light-duty vehicle CO$_2$ emissions (vehicle only) and fuel consumption, efficiency and reference cases*

	CO$_2$ emissions (Mt)				Energy use (EJ)			
	2000	2030			2000	2030		
		Reference	High	Medium		Reference	High	Medium
OECD North America	1226	1623	1178	1392	17.7	23.4	17.0	20.0
OECD Europe	488	535	431	479	7.0	7.5	6.0	6.7
OECD Pacific	220	219	176	197	3.2	3.2	2.6	2.9
EECCA	84	229	188	209	1.2	3.3	2.7	3.0
Eastern Europe	49	82	68	74	0.7	1.2	1.0	1.0
China	46	303	267	287	0.7	4.4	3.8	4.1
Other Asia	54	174	148	160	0.8	2.5	2.1	2.3
India	22	103	87	95	0.3	1.5	1.2	1.4
Middle East	27	67	57	62	0.4	1.0	0.8	0.9
Latin America	110	294	251	273	1.6	4.2	3.6	3.9
Africa	53	167	152	162	0.8	2.4	2.2	2.3
Total	2379	3797	3004	3390	34.2	54.4	43.1	48.6

Note: EECCA = countries of EasternEurope, the Caucasus and Central Asia.

Table 5.11: *Cost of CO$_2$ reduction in new 2030 LDVs*

	CO$_2$ reduction cost (US$/tCO$_2$)							
	High efficiency case				Medium efficiency case			
	30 US$/bbl 0.39 US$/L	40 US$/bbl 0.45 US$/L	50 US$/bbl 0.51 US$/L	60 US$/bbl 0.60 US$/L	30 US$/bbl 0.39 US$/L	40 US$/bbl 0.45 US$/L	50 US$/bbl 0.51 US$/L	60 US$/bbl 0.60 US$/L
OECD North America	5	-16	-37	-68	-72	-93	-114	-146
OECD Europe	131	110	89	58	14	-7	-28	-60
OECD Pacific	231	210	189	157	-14	-36	-57	-88
EECCA	81	60	39	8	-54	-76	-97	-128
Eastern Europe	181	160	139	107	-18	-39	-60	-92
China	23	2	-19	-51	-23	-44	-65	-97
Other Asia	19	-2	-23	-55	-23	-44	-65	-96
India	62	41	20	-12	9	-12	-33	-65
Middle East	-15	-36	-57	-89	-49	-70	-91	-122
Latin America	-6	-27	-48	-79	-42	-63	-84	-116
Africa	10	-12	-33	-64	-33	-54	-75	-106

Note: EECCA = countries of EasternEurope, the Caucasus and Central Asia.

(<100 US$/tCO$_2$) potential is available at a net savings over the vehicle lifetime; at 40 US$/bbl, over 90% of the 718 Mt total potential is available at a net savings.

The regional detail, not shown in Table 5.12, is illuminating. In the High Efficiency scenario, of 793 Mt of total potential,

445 Mt are in OECD North America and are available at a net savings at 40 US$/bbl oil (and at less than 20 US$/tCO$_2$ at 30 US$/bbl oil). The next highest regional potential is in OECD Europe at 104 Mt, but this potential is more expensive: at 30 US$/bbl oil. Only 56 Mt is available below 100 US$/tCO$_2$, and becomes available at below 100 US$/tCO$_2$ only at 60 US$/bbl

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37 These results do not take account of the effect higher oil prices would have on LDV efficiency in the Reference Scenario. This efficiency level would be expected to be a strong function of oil price, that is, it would be higher for higher prices. Consequently, the technology cost of improving vehicle efficiency further would also be higher – reducing the economic potential.
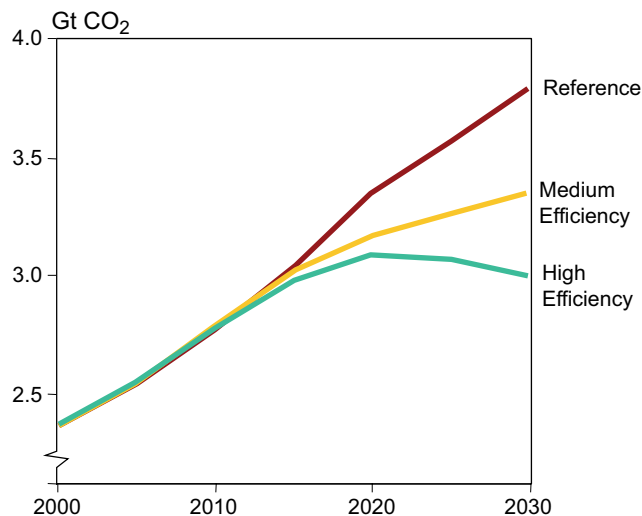
Figure 5.16: *Light-duty vehicle CO_2 emissions for three scenarios*

oil. China has the next highest total emissions (2030 Reference case emissions of 303 Mt) but only a moderate potential of 36 Mt. This potential is fully available at a net savings only if oil is 50 US\$/bbl or higher – perhaps not surprising because China has ambitious fuel economy standards embedded in the Reference Case and has relatively low driving rates, which make further improvements more difficult and expensive.

5.4.2.2   Aircraft

QinetiQ (UK)[38] analysed the fuel consumption and CO_2 trends for a simple global aviation growth scenario to provide an indicative view on the extent that technology and other developments might mitigate aviation emissions. The ICAO traffic forecast (ICAO/FESG, 2003) defined traffic growth to 2030 from which a future fleet composition was developed, using a range of current and future aircraft types where their introduction could be assumed, as well as representative aircraft types based on seat capacity. Fuel burn and emissions were calculated using known emissions performance and projections for future aircraft where necessary.

The analysis assumed a range of technology options as follows:
* Case 1 assumed no technology change from 2002 to 2030; using the extrapolated traffic forecast from ICAO FESG – this case shows only the effects of traffic growth on emissions.
* Case 2 – as Case 1, but assumes all new aircraft deliveries after 2005 would be 'best available technology at a 2005 (BAT)' performance standard, and with specific new aircraft (A380, A350, B787) delivered from 2008.
* Case 3 – as Case 1, but with assumed annual fleet fuel efficiency improvements as per 'Greene' and DTI (IPCC

1999, Chapter 9, Table 9.15). This assumes a fleet efficiency improvement trend of 1.3% per year to 2010, assumed then to decline to 1.0% per year to 2020 and 0.5% per year thereafter. This is the reference case.
* Case 4 – as Case 3, plus the assumption that a 50 US\$/tCO_2 cost will produce a further 0.5% fuel efficiency improvement per annum from 2005, as suggested by the cost-potential estimates of Wit *et al.*, (2002), that assume technologies such as winglets, fuselage skin treatments (riblets) and further weight reductions and engine developments will be introduced by airlines.
* Case 5 – as Case 3, plus the assumption of 100 US\$/tCO_2 cost, producing a 1.0% fuel efficiency improvement per annum from 2005 (Wit *et al.*, 2002), again influencing the introduction of additional technologies as above.

The results of this analysis are summarised in Table 5.13.

Case 2 is a simple representation of planned industry developments and shows their effect to 2030, ignoring further technology developments. This is an artificial case, as on-going efficiency improvements would occur as a matter of course, but it shows that these planned fleet developments alone might save 14% of the CO_2 that the 'no technology change' of Case 1 would have produced. Case 3 should be regarded as the 'base case' from which benefits are measured, as this case reflects an agreed fuel efficiency trend assumed for some of the calculations produced in the IPCC Special Report (1999). This results in a further 11% reduction in CO_2 by 2030 compared with Case 2. Cases 4 and 5 assume that a carbon cost will drive additional technology developments from 2005 – no additional demand effect has been assumed. These show further CO_2 reduction of 11.8% and 22.2% compared with 'base case' 3 over the same period from technologies that are assumed to be more attractive than hitherto. However, even the most ambitious scenario suggests that CO_2 production will increase by almost 100% from the base year. The cost potentials for Cases 4 and 5 are based on one study and further studies may refine these results. There is limited literature in the public domain on costs of mitigation technologies. The effects of more advanced technology developments, such as the blended wing body, are not modelled here, as these developments are assumed to take place after 2030.

The analysis suggests that aviation emissions will continue to grow as a result of continued demand for civil aviation. Assuming the historical fuel efficiency trend produced by industry developments will continue (albeit at a declining level), carbon emissions will also grow, but at a lower rate than traffic. Carbon pricing could effect further emissions reductions if the aviation industry introduces further technology measures in response.

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38 http://www.dti.gov.uk/files/file35675.pdf

Table 5.12: *Economic potential of LDV mitigation technologies as a function of world oil price, for new vehicles in 2030*

World oil price (US$/bbl)	Region	Economic potential (MtCO$_2$)				
		Cost ranges (US$/tCO$_2$)				
		<100	<0	0-20	20-50	50-100
30	OECD	523	253	270	0	0
	EIT	49	28	0	0	21
	Other	146	88	30	20	8
	World	718	369	300	20	29
40	OECD	523	523	0	0	0
	EIT	49	28	0	0	21
	Other	146	118	20	8	0
	World	718	669	20	8	21
50	OECD	571	523	0	0	48
	EIT	49	28	0	21	0
	Other	146	138	8	0	0
	World	766	689	8	21	48
60	OECD	571	523	0	0	48
	EIT	49	28	21	0	0
	Other	146	146	0	0	0
	World	766	697	21	0	48

5.4.2.3   Biofuels

IEA has projected the potential worldwide increased use of biofuels in the transport sector assuming successful technology development and policy measures reducing barriers to biomass deployment and providing economic incentives.

IEA's *World Energy Outlook 2006* (IEA, 2006b) develops an Alternative policy scenario that adds 55 Mtoe biofuels above baseline levels of 92 Mtoe by 2030, which increases the biofuels share of total transport fuel demand from 3 to 5%. In this scenario, all of the biofuels are produced by conventional technology, that is ethanol from starch and sugar crops and biodiesel from oil crops. Assuming an average CO$_2$ reduction from gasoline use of 25%,[39] this would reduce transport CO$_2$ emissions by 36 Mt.

Furthermore, according to the Beyond the Alternative policy scenario (BAPS), which assumed more energy savings and emission reductions through a set of technological

breakthroughs, biofuels use in road transport would double compared to the Alternative policy scenario.

A second IEA report, Energy Technology Perspectives 2006 (IEA, 2006a), evaluates a series of more ambitious scenarios that yield biomass displacement of 13–25% of transport energy demand by 2050, compared to Baseline levels of 3% displacement. Two scenarios, called Accelerated Technology (ACT) Map and TECH Plus, assume economic incentives equivalent to 25 US$/tCO$_2$, increased support for research and development, demonstration, and deployment programmes, and policy instruments to overcome commercialization barriers. Both scenarios have optimistic assumptions about the success of efforts to reduce fuel production costs, increase crop yields, and so forth. In the ACT Map scenario, transport biofuels production reaches 480 Mtoe in 2050, accounting for 13% of total transport demand; in TECH Plus, biofuels represents 25% of transport energy demand by 2050. These displacements yield CO$_2$ reductions (below the Baseline levels) of 1800 MtCO$_2$ in Map and 2300 MtCO$_2$ in TECH Plus, with the major

Table 5.13: *Summaries of CO$_2$ mitigation potential analysis in aviation*

Aviation technology	2002 CO$_2$ (Mt)	2030 CO$_2$ (Mt)	Ratio (2030/2002)
Case 1 (no technological change)	489.29	1,609.74	3.29
Case 2 (BAT new aircrafts)	489.29	1,395.06	2.85
Case 3 (base)	489.29	1,247.02 (100%)	2.55
Case 4 (50 US$/tCO$_2$-eq)	489.29	1,100.15 (88%)	2.25
Case 5 (100 US$/tCO$_2$-eq)	489.29	969.96 (78%)	1.98

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39 IEA cites the following estimates for biofuels CO$_2$ reduction when used as a replacement fuel: Corn in the U.S., –13%; ethanol in Europe, –30%; ethanol in Brazil, –90%; sugar beets to ethanol in Europe, –40 to –60%; rapeseed-derived biodiesel in Europe, –40 to –60%.
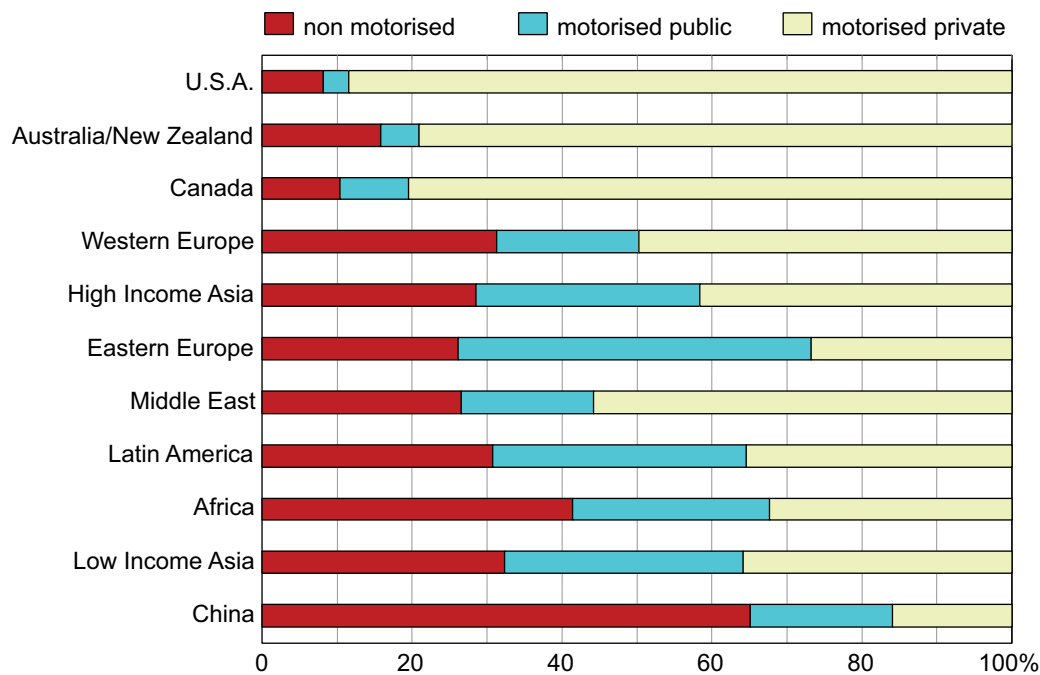
Figure 5.17: *Modal split for the cities represented in the Millennium Cities Database for Sustainable Transport by region*
Source: Kenworthy & Laube, 2002.

Income plays a central role in explaining motorization. But cities of similar wealth often have very different rates of motorizsation. Mode shares vary dramatically across cities, even within single countries. The share of trips by walking, cycling and public transport is 50% or higher in most Asian, African and Latin American cities, and even in Japan and Western Europe (Figure 5.17). Coordination of land use and transport planning is key to maintaining these high mode shares.

Kenworthy and Laube (1999) pointed out that high urban densities are associated with lower levels of car ownership and car use and higher levels of transit use. These densities are decreasing almost everywhere. Perhaps the most important strategy and highest priority to slow motorization is to strengthen local institutions, particularly in urban areas (Sperling and Salon, 2002).

Some Asian cities with strong governments, especially Hong Kong, Singapore and Shanghai are actively and effectively pursuing strategies to slow motorization by providing high quality public transport and coordinating land use and transport planning (Cullinane, 2002; Willoughby, 2001; Cameron *et al.*, 2004; Sperling and Salon, 2002).

There are many other examples of successfully integrated land use and transport planning, including Stockholm and Portland, Oregon (USA) (Abbott, 2002; Lundqvist, 2003). They mostly couple mixed-use and compact land use development with better public transport access to minimize auto dependence. The effectiveness of these initiatives in reducing sprawl is the subject of debate, especially in the USA (Song and Knaap, 2004; Gordon and Richardson, 1997; Ewing, 1997). There are several

arguments that the settlement pattern is largely determined, so changes in land use are marginal, or that travel behaviour may be more susceptible to policy interventions than land-use preferences (Richardson and Bae, 2004). Ewing and Cervero (2001) found that typical elasticity of vehicle-km travelled with respect to local density is –0.05, while Pickrell (1999) noted that reduction in auto use become significant only at densities of 4000 people or more per square kilometre – densities rarely observed in US suburbs, but often reached elsewhere (Newman and Kenworthy, 1999). Coordinated transport and land-use methods might have greater benefits in the developing world where dense mixed land use prevails and car ownership rate is low. Curitiba is a prime example of coordinated citywide transport and land-use planning (Gilat and Sussman, 2003; Cervero, 1998).

The effectiveness of policies in shifting passengers from cars to buses and rails is uncertain. The literature on elasticity with respect to other prices (cross price elasticity) is not abundant and likely to vary according to the context (Hensher, 2001). The Transport Research Laboratory guide showed several cross price elasticity estimates with considerable variance in preceding studies (TRL, 2004). Goodwin (1992) gave an average cross elasticity of public transport demand with respect to petrol prices of +0.34. Jong and Gunn (2001) also gave an average cross elasticity of public transport trips with respect to fuel price and car time of +0.33 and +0.27 in the short term and +0.07 and +0.15 in the long term.

The literature on mode shifts from cars to new rail services is also limited. A monitoring study of Manchester indicated that about 11% of the passengers on the new light rail would have

Table 5.14: *Taxes and pricing in the transport sector in developing and developed countries*

Instrument	Developing countries/EIT	Developed countries
Tax incentives to promote use of natural gas	Pakistan, Argentina, Colombia, Russia	Italy, Germany, Australia, Ireland, Canada, UK, Belgium
Incentives to promote natural gas vehicles	Malaysia, Egypt	Belgium, UK, USA, Australia, Ireland
Annual road tax differentiated by vintage	Singapore and India (fixed span and scrapping)	Germany
Emission trading	Chile	
Congestion pricing including Area Licensing Scheme; vehicle registration fees; annual circulation tax	Chile, Singapore	Norway, Belgium
Vehicle taxes based on emissions-tax deductions on cleaner cars e.g., battery operated or alternative fuel vehicles	South Korea	Austria, Britain, Belgium, Germany, Japan, The Netherlands, Sweden
Carbon tax by size of engine	Zimbabwe	
Cross subsidization of cleaner fuels (ethanol blending by gasoline tax - through imposition of lower surcharge or excise duty exemption)	India	

Source: Adapted from Pandey and Bhardwaj, 2000; Gupta, 1999 and European Natural Gas Vehicle Association, 2002.

otherwise used their cars for their trips (Mackett and Edwards, 1998), while a Japanese study of four domestic rails and monorails showed that 10–30% of passengers on these modes were diverted from car mode. The majority of the passengers were transferred from alternative bus and rail routes (Japanese Ministry of Land, Infrastructure and Transport and Institute of Highway Economics, 2004). The Transport Research Laboratory guide (2004) contained international evidence of diversion rates from car to new urban rail ranging from 5–30%. These diversion rates are partly related to car mode share, in the sense that car share is so high in the USA and Australia that ridership on new rail systems is more likely to come from cars in those countries (Booz Allen & Hamilton 1999, cited in Transport Research Laboratory, 2004). It is also known that patronage of metros for cities in the developing world has been drawn almost exclusively from existing public transport users or through generation effects (Fouracre *et al.*, 2003).

The literature suggests that in general, single policies or initiatives tend to have a rather modest effect on the motorization process. The key to restraining motorization is to cluster a number of initiatives and policies, including improved transit service, improved facilities for NMT (Non-motorized transport) and market and regulatory instruments to restrain car ownership and use (Sperling and Salon, 2002). Various pricing and regulatory instruments are addressed below.

Investment appraisal is an important issue in transport planning and policy. The most widely applied appraisal technique in transport is cost benefit analysis (CBA) (Nijkamp *et al.*, 2003). In CBA, the cost of CO_2 emissions can be indirectly included in the vehicle operating cost or directly counted at an estimated price, but some form of robustness testing is useful in the latter case. Alternatively, the amount of CO_2 emissions is listed on an appraisal summary table of Multi-Criteria Analysis (MCA) as a part of non-monetized benefits and costs (Mackie and Nellthorp, 2001; Grant-Muller *et al.*, 2001; Forkenbrock and Weisbrod, 2001; Japanese Study Group on Road Investment Evaluation, 2000). To the extent that the cost of CO_2 emissions has a relatively important weight in these assessments, investments in unnecessarily carbon-intensive projects might be avoided. Strategic CBA can further make transport planning and policy carbon-efficient by extending CBA to cover multi-modal investment alternatives, while Strategic Environmental Assessment (SEA) can accomplish it by including multi-sector elements. (ECMT, 2000; ECMT, 2004b).

5.5.1.2   *Taxation and pricing*

Transport pricing refers to the collection of measures used to alter market prices by influencing the purchase or use of a vehicle. Typically measures applied to road transport are fuel pricing and taxation, vehicle license/registration fees, annual circulation taxes, tolls and road charges and parking charges. Table 5.14 presents an overview of examples of taxes and pricing measures that have been applied in some developing and developed countries.

Pricing, taxes and charges, apart from raising revenue for governments, are expected to influence travel demand and hence fuel demand and it is on this basis that GHG reduction can be realized.

Transport pricing can offer important gains in social welfare. For the UK, France and Germany together, (OECD, 2003) estimates net welfare gains to society of optimal charges (set at the marginal social cost level) at over 20 billion €/yr (22.6 US$/yr).

Box 5.6 Examples of pricing policies for heavy-duty vehicles

Switzerland: In January 2001, trucks of maximum 35 tonnes weight were allowed on Swiss territory (previously 28 tonnes) and a tax of 1.00 cent/tkm (for the vehicle middle emission category) was imposed on trucks above 3.5 tonnes on all roads. It replaced a previous fixed tax on heavy-duty vehicles. The tax is raised electronically. Since 2005, the tax is higher at 1.60 cent/tkm, but 40 tonnes trucks are allowed. Over the period 2001–2003, it was estimated that it contributed to an 11.9% decrease in vehicle-km and a 3.5% decrease in tonnes-km of domestic traffic. The tax led to an improved carriers' productivity and it is anticipated that, for that reason, emissions of CO_2 and NO_x would decrease over the period 2001–2007 by 6–8%. On the other hand transit traffic, which amounts to 10% of total traffic, was also affected in a similar way by the new tax regime, so that the number of HDL has been decreasing at a rate of about 2–3% per year, while, at the same time, increasing in terms of tonnes-km (ARE, 2004b; 2006). A part of the revenues are used to finance improvements to the rail network.

Germany: A new toll system was introduced in January 2005 for all trucks with a maximum weight of 12 tonnes and above. This so-called LKW-MAUT tax is levied on superhighways on the base of the distance driven; its cost varies between 9 and 14 Eurocents according to the number of axles and the emission category of the truck. Payments are made via a GPS system, at manual payment terminals or by Internet. The receipts will be used to improve the transport networks of Germany. The system introduction appears successful, but it is too early to assess its impacts.

Although the focus here is on transport pricing options to limit CO_2 emissions, it should be recognized that many projects and policies with that effect are not focused on GHG emissions but rather on other objectives. A pricing policy may well aim simultaneously at reducing local pollution and GHG emissions, accidents, noise and congestion, as well as generating State revenue for enlarging of social welfare and/or infrastructure construction and maintenance. Every benefit with respect to these objectives may then be assessed simultaneously through CBA or MCA; they may be called co-benefits. Governments can take these co-benefits into account when considering the introduction of transport pricing such as for fuel. This is all the more important since a project could be not worth realising if only one particular benefit is considered, whereas it could very well be proved beneficial when adding all the co-benefits.

Taxes

Empirically, throughout the last 30 years, regions with relatively low fuel prices have low fuel economy (USA, Canada, Australia) and regions where relatively high fuel prices apply (due to fuel taxes) have better car fuel economy (Japan and European countries). For example, fuel taxes are about 8 times higher in the UK than in the USA, resulting in fuel prices that are about three times higher. UK vehicles are about twice as fuel-efficient; mileage travelled is about 20% lower and vehicle ownership is lower as well. This also results in lower average per capita fuel expenditures. Clearly, automobile use is sensitive to cost differences in the long run (VTPI, 2005). In theory, long run impact of increases in fuel prices on fuel consumption are likely to be about 2 to 3 times greater than short run impact (VTPI, 2005). Based on the price elasticities (Goodwin et al., 2004) judged to be the best defined results for developed countries, if the real price of fuel rises by 10% and stays at that level, the volume of fuel consumed by road vehicles will fall by about 2.5% within a year, building up to a reduction of over 6% in the longer run (about 5 years or so), as shown in Table 5.15.

An important reason why a fuel or CO_2 tax would have limited effects is that price elasticities tend to be substantially smaller than the income elasticities of demand. In the long run the income elasticity of demand is a factor 1.5–3 higher than the price elasticity of total transport demand (Goodwin et al., 2004). In developing countries, where incomes are lower, the demand response to price changes may be significantly more elastic.

Recent evidence suggests that the effect of CO_2 taxes and high fuel prices may be having a shrinking effect in the more car-dependent societies. While the evidence is solid that price elasticities indicated in Table 5.15 and used by Goodwin were indeed around –0.25 (i.e., 2.5% reduction in fuel for every 10% increase in price), in earlier years, new evidence indicates a quite different story. Small and Van Dender (2007) found that price elasticities in the USA dropped to about –0.11 in the late 1990s, and Hughes et al. (2006) found that they dropped even further in 2001–2006, to about –0.04. The explanation seems to be that people in the USA have become so dependent on their vehicles that they have little choice but to adapt to higher prices. One might argue that these are short term elasticities, but the erratic nature of gasoline prices in the USA (and the world) result in drivers never exhibiting long-term behavior. Prices drop before they seriously consider changing work or home locations or even buying more efficient vehicles. If oil prices continue to cycle up and down, as many expect, drivers may continue to cling to their current behaviors. If so, CO_2 taxes would have small and shrinking effects in the USA and other countries where cars are most common.

Table 5.15: *Impact of a permanent increase in real fuel prices by 10%*

	Short run/within 1 year (%)	Long run/5 years (%)
Traffic volume	-1	-3
Fuel consumption	-2.5	-6
Vehicle fuel efficiency	-1.5	-4
Vehicle ownership	Less than -1	-2.5

Source: Goodwin et al. 2004.

As an alternative to fuel taxes, registration and circulation taxes can be used to incentivise the purchase (directly) and manufacturing (indirectly) of fuel-efficient cars. This could be done through a revenue neutral fee system, where fuel-efficient cars receive a rebate and guzzler cars are faced with an extra fee. There is evidence that incentives given through registration taxes are more effective than incentives given through annual circulation taxes (Annema *et al.*, 2001). Buyers of new cars do not expect to be able to pass on increased registration taxes when selling the vehicle. Due to refunds on registration taxes for cars that were relatively fuel efficient compared to similar sized cars, the percentage of cars sold in the two most fuel efficient classes increased from 0.3%–3.2% (cars over 20% more fuel efficient than average) and from 9.5%–16.1% (for cars between 10 and 20% more fuel efficient than average) in the Netherlands (ADAC, 2005). After the abolishment of the refunds, shares decreased again. COWI (2002) modelled the impact on fuel efficiency of reforming current registration and circulation taxes so they would depend fully on the CO_2 emissions of new cars. Calculated reduction percentages varied from 3.3–8.5% for 9 European countries, depending on their current tax bases.

Niederberger (2005) outlines a voluntary agreement with the Swiss government under which the oil industry took responsibility for GHG emissions from the road transport sector, which they supply with fuel. As of 1 October 2005, Swiss oil importers voluntarily contribute the equivalent of about 5 cents per gallon (approx. 80 million US$ annually) into a climate protection fund that is invested via a non-profit (non-governmental) foundation into climate mitigation projects domestically and abroad (via the emerging carbon market mechanisms of the Kyoto Protocol). Cost savings (compared with an incentive tax) are huge and the private sector is in charge of investing the funds effectively. A similar system in the USA could generate 9 billion US$ in funds annually to incentivize clean alternative fuels and energy efficient vehicles, which could lower US dependency on foreign fuel sources. This policy is also credible from a sustainable development perspective than the alternative CO_2 tax, since the high CO_2 tax would have led to large-scale shifts in tank tourism – and bookkeeping GHG reductions for Switzerland – although the real reductions would have been less than half of the total effect and neighbouring countries would have been left with the excess emissions.

Licensing and parking charges

The most renowned area licensing and parking charges scheme has been applied in Singapore with effective reduction in total vehicular traffic and hence energy (petroleum) demand (Fwa, 2002). The area licensing scheme in Singapore resulted in 1.043 GJ per day energy savings with private vehicular traffic reducing by 75% (Fwa, 2002).

Unfortunately there is currently a lack of data on potential GHG savings associated with policy, institutional and fiscal reforms/measures with respect to transport particularly in other developing countries. General estimates of reduction in use of private vehicle operators resulting from fuel pricing and taxing are 15–20% (World Bank, 2002; Martin *et al.*, 1995).

Table 5.16: *Potential energy and GHG savings from pricing, taxes and charges for road transport*

Tax/pricing measure	Potential energy/GHG savings or transport improvements	Reference
Optimal road pricing based on congestion charging (London, UK)	20% reduction in CO_2 emissions as a result of 18% reduction in traffic	Transport for London (2005)
Congestion pricing of the Namsan Tunnels (Seoul, South Korea)	34% reduction of peak passenger traffic volume. Traffic flow from 20 to 30 km/hr.	World Bank (2002)
Fuel pricing and taxation	15-20% for vehicle operators.	Martin et al. (1995)
Area Licensing Scheme (Singapore)	1.043 GJ/day energy savings. Vehicular traffic reduced by 50%. Private traffic reduced by 75%. Travel speed increased 20 to 33 km/hr.	Fwa (2002)
Urban gasoline tax (Canada)	1.4 Mton by 2010 2.6 Mton by 2020	Transportation in Canada; www.tc.gc. ca/pol/en/Report/anre1999/tc9905be.htm
Congestion charge trial in Stockholm (2005-2006)	13% reduction of CO_2	http://www.stockholmsforsoket.se/ templates/page.aspx?id=2453

Box 5.7 Policies to promote biofuels

Policies to promote biofuels are prominent in national emissions abatement strategies. Since benefits of biofuels for CO_2 mitigation mainly come from the well-to-tank part, incentives for biofuels are more effective climate policies if they are tied to the whole well-to-wheels CO_2 efficiencies. Thus preferential tax rates, subsi-dies and quotas for fuel blending should be calibrated to the benefits in terms of net CO_2 savings over the whole well-to-wheel cycle associated with each fuel. Development of an index of CO_2 savings by fuel type would be useful and if agreed internationally could help to liberalise markets for new fuels. Indexing incentives would also help to avoid discrimination between feedstocks. Subsidies that support production of specific crops risk being counterproductive to emission policies in the long run (ECMT, 2007). In order to avoid negative effects of biofuel production on sustainable development (e.g. biodiversity impacts), additional conditions could be tied to incentives for biofuels.

The following incentives for biofuels are implemented or in the policy pipeline (Hamelinck, *et al*. 2005):
Brazil was one of the first countries to implement policies to stimulate biofuel consumption. Currently, flexible fuel vehicles are eligible for federal value-added tax reductions ranging from 15–28%. In addition, all gasoline should meet a legal alcohol content requirement of 20–24%.

Motivated by the biofuels directive in the European Union, the EU member states have implemented a variety of policies. Most of the member states have implemented an excise duty relief. Austria, Spain, Sweden, the Netherlands and the UK have implemented an obligation or intend to implement an obligation in the coming years. Sweden and Austria also implemented a CO_2 tax.

The American Jobs creation act of 2004 provides tax incentives for alcohol and biodiesel fuels. The credits have been set at 0.5–1 US$/gallon (about 0.11–0.21 €/litre). Some 39 states have developed additional policy programmes or mechanisms to support the increase use of biofuel. The types of measures range from tax exemptions on resources required to manufacturing or distributing biofuels (e.g. labour, buildings); have obligatory targets for governmental fleets and provide tax exemptions or subsidies when purchasing more flexible vehicles. One estimate is that total subsidies in the US for biofuels were 5.1–6.8 billion US$ in 2006, about half in the form of fuel excise tax reductions, and another substantial amount for growing corn used for ethanol.

New blending mandates have also appeared in China, Canada, Colombia, Malaysia and Thailand. Four provinces in China added dates for blending in major cities, bringing to nine the number of provinces with blending mandates (REN21, 2006).

5.5.1.3   *Regulatory and operational measures*

Although pricing and fiscal instruments are obvious tools for government policy, they are often not very effective, as reflected by the potential reduction in fuel savings (IEA, 2003). Potential effective (and cost-effective) non-fiscal measures that can be effective in an oil crisis are regulatory measures such as:
• Lower speed limits on motorways;
• High occupancy vehicle requirements for certain roads and networks;
• Vehicle maintenance requirements;
• Odd/even number plate and other driving restrictions;
• Providing information on CO_2 emission performances of vehicles (labelling);
• Establishing carbon standards for fuels;
• Direct traffic restrictions (e.g., no entry into business district);
• Free/expanded urban public transport;
• Encouraging alternatives to travel (e.g., greater telecommuting);
• Emergency switching from road to rail freight;
• Reducing congestion through removal of night-time/ weekend driving bans for freight.

IEA (2003) indicates that such measures could contribute to significant oil savings. This is a typical case where a portfolio of measures is applied together and they would work well with adequate systems of monitoring and enforcement.

For the measures to be implemented effectively considerable preparatory work is necessary and Table 5.17 shows examples of what could be done to ensure the measures proposed above can be effective in oil savings.

The combined effect of these regulatory measures used to target light-duty vehicles (in addition to blending non-petroleum fuels with gasoline and diesel) is estimated to be a reduction of 15% of daily fuel consumption.

In OECD countries vehicles consume 10–20% more fuel per km than indicated by their rated efficiency. It is estimated that 5–10% reduction in fuel consumption can be achieved by stronger inspection and vehicle maintenance programmes, adoption of on board technologies, more widespread driver training and better enforcement and control of vehicle speeds.

Table 5.17: *Preparations required to implement some regulatory measures*

Measure to be implemented	Preparatory work
Speed limits[a]	• Install electronic speed limit system • Change the law
Carpool days	• System of finding rides • Car parks • High occupancy car lanes
Energy efficient car and driving choice from home	• On board efficient indicator systems • Driver training • Information on efficient car purchases
Telecommuting days	• Telecommuting programmes and protocols • Practice
Clean car choice	• Public awareness of car consumption • Labeling based on CO_2 performance
Car free days	• Biking/walking/transit facilities • Home/job commuting reduced

a) The Swedish road administration has calculated the effect of regulatory measures on speed. Exceeding speed limits on the Swedish road network gives an extra CO_2 emission of 0.7Mt on an annual basis (compared to total emissions of 20 Mt). A large part of this can be tackled using speed cameras and in the future intelligent speed adaptation in vehicles. Besides this, reduction of speed limits (by 10 km/h except for the least densely populated areas where there is no alternative to the private car) could result in a similar amount of CO_2 reduction.

Source: Adapted from IEA, 2003.

Vehicle travel demand can be reduced by 10–15% by aggressively combining infrastructure improvements, intelligent transport technologies and systems (e.g., better routing systems and congestion reduction), information systems and better transit systems in addition to road pricing.

Another regulatory approach, under consideration in California as part of its 2006 Global Warming Solutions Act, is carbon-based fuel standards. Fuel suppliers would be required to reduce the carbon content of their fuels according to a tightening schedule. For instance, gasoline from conventional oil would be rated at 1.0, ethanol from corn and natural gas at 0.8, electricity for vehicles at 0.6 and so on. The fuel suppliers would be allowed to trade and bank credits and car makers would be required to produce vehicles at an amount that corresponds to the planned sales of alternative fuels. Reductions of 5% or more in transport fuel GHGs by 2020 are envisioned, with much greater reductions in later years.

5.5.1.4   *Fuel economy standards – road transport*

Most industrialized nations now impose fuel economy requirements (or their equivalent in CO_2 emissions requirements)

on new light-duty vehicles (Plotkin, 2004; An and Sauer, 2004). The first standards were imposed by the United States in 1975, requiring 27.5 mpg (8.55 L/100 km) corporate fleet averages for new passenger cars and 20.7 mpg (11.36 L/100 km) for light trucks (based on tests instituted by the US Environmental Protection Agency, using the 'CAFE' driving cycle) by 1985. The passenger car standard remains unchanged, whereas the light truck standard has recently been increased to 22.2 mpg (10.6 L/100 km) for the 2007 model year and to 23.5 mpg (10.0 L/100 km) in model year 2010.[40] Additional standards (some voluntary) include:

- European Union: a 2008 fleet wide requirement[41] of 140 gCO_2/km, about 41 mpg (5.74 L/100 km) of gasoline equivalent, using the New European Driving Cycle (NEDC), based on a Voluntary Agreement between the EU and the European manufacturers, with the Korean and Japanese manufacturers following in 2009. Recent slowing of the rate of efficiency improvement has raised doubts that the manufacturers will achieve the 2008 and 2009 targets (Kageson, 2005).
- Japan: a 2010 target of about 35.5 mpg (6.6 L/100 km) for new gasoline passenger vehicles, using the Japan 10/15 driving cycle based on weight-class standards.
- China: weight-class standards that are applied to each new vehicle using the NEDC driving cycle, with target years of 2005 and 2008. At the historical mix of vehicles, the standards are equivalent to fleet targets of about 30.4 mpg (7.7 L/100 km) by 2005 and 32.5 mpg (7.2 L/100 km) by 2008 (An and Sauer, 2004).
- Australia: a 2010 target for new vehicles of 18% reduction in average fuel consumption relative to the 2002 passenger car fleet, corresponding to 6.8 L/100 km, or 34.6 mpg. (DfT, 2003), based on a voluntary agreement between industry and government.
- The State of California has established GHG emission standards for new light-duty vehicles designed to reduce per-vehicle emissions by 22% in 2012 and 30% by 2016. Several US states have decided to adopt these standards, as well. At the time of writing, US industry and the federal government were fighting these standards in the courts.

The NEDC and Japan 10/15 driving cycles are slower than the US CAFE cycle and, for most vehicles (though probably not for hybrids), will yield lower measured fuel economy levels than the CAFE cycle for the same vehicles. Consequently, if they reach their targets, the EU, Japanese and Chinese fleets are likely to achieve fuel economies higher than implied by the values above if measured on the US test. A suggested correction factor (for the undiscounted test results) is 1.13 for the EU and China and 1.35 for Japan (An and Sauer, 2004), though these are likely to be at the high end of the possible range of values

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40 In 2011, manufacturers must comply with a reformed system where required CAFE levels depend on the manufacturer's fleet mix based on vehicle "footprint," or track width wheelbase (NHTSA CAFE website, 2006).
41 There are no specific corporate requirements for the entire new light-duty vehicle fleet.
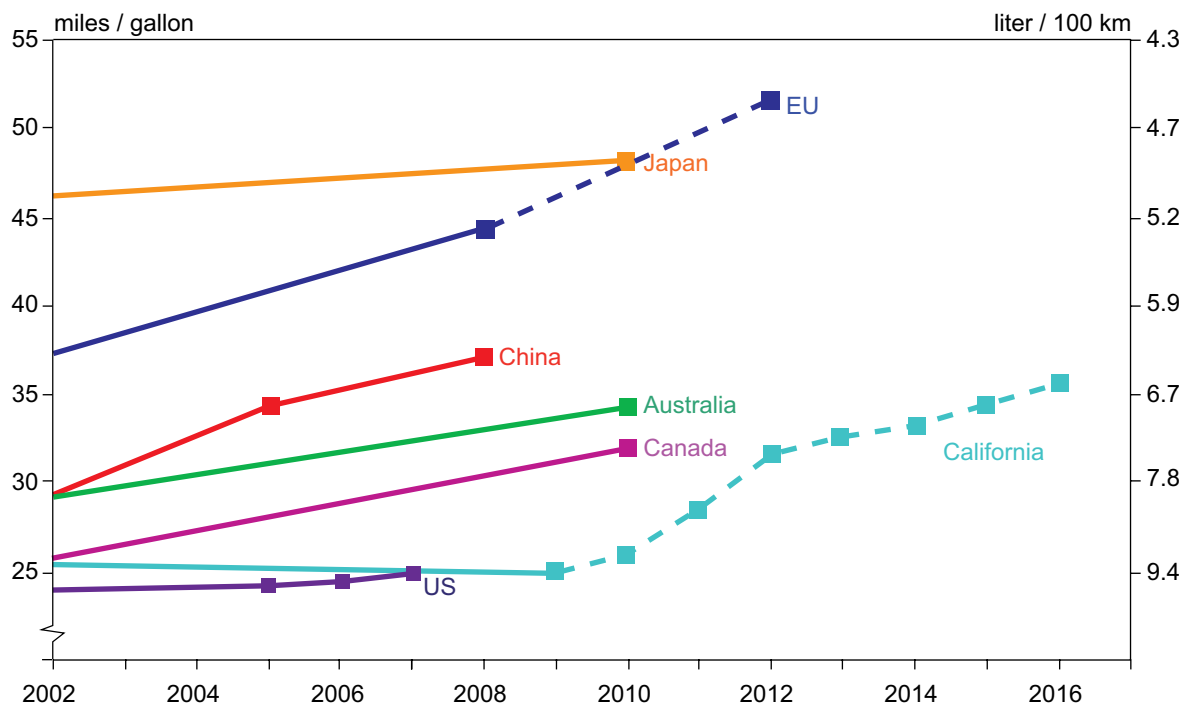
Figure 5.18: *Fuel economy and GHG emission standards*

Note: all the fuel economy targets represent test values based on artificial driving cycles. The standards in the EU and Australia are based on voluntary agreements. In most cases, actual on-road fuel economy values will be lower; for example, the US publishes fuel economy estimates for individual LDVs that are about 15% lower than the test val-ues and even these values appear to be optimistic. Miles/gallon is per US gallon.

for such factors.[42] Figure 5.18 shows the 'corrected' comparison of standards.

Recent studies of the costs and fuel savings potential of technology improvements indicate considerable opportunity to achieve further fleet fuel economy gains from more stringent standards. For example, the US National Research Council (NRC, 2002) estimates that US light-duty vehicle fuel economy can be increased by 25–33% within 15 years with existing technologies that cost less than the value of fuel saved. A study by Ricardo Consulting Engineers for the UK Department for Transport (Owen and Gordon, 2002) develops a step-wise series of improvements in a baseline diesel passenger car that yields a 38% reduction in CO_2 emissions (a 61% increase in fuel economy), to 92 g/km, by 2013 using parallel hybrid technology at an incremental cost of 2300–3,100 £ (4200–5700 US$) with a 15,300 £ (28,000 US$) baseline vehicle. Even where fuel savings will outweigh the cost of new technologies, however, the market will not necessarily adopt these technologies by itself (or achieve the maximum fuel economy benefits from the technologies even if they are adopted). Two crucial deterrents are, first, that the buyers of new vehicles tend to consider only the first three years or so of fuel savings (NRC, 2002; Annema *et al.*, 2001), and second, that vehicle buyers will take some

of the benefits of the technologies in higher power and greater size rather than in improved fuel economy. Further, potential benefits for consumers over the vehicle's lifetime are generally small, while risks for producers are high (Greene, 2005). Also, neither the purchasers of new vehicles nor their manufacturers will take into account the climate effects of the vehicles.

Strong criticisms have been raised about fuel economy standards, particularly concerning claimed adverse safety implications of weight reductions supposedly demanded by higher standards and increased driving caused by the lower fuel costs (per mile or km) associated with higher fuel economy.

The safety debate is complex and not easily summarized. Although there is no doubt that adding weight to a vehicle improves its safety in some types of crashes, it does so at the expense of other vehicles; further, heavy light trucks have been shown to be no safer, and in some cases less safe than lighter passenger cars, primarily because of their high rollover risk (Ross *et al.*, 2006). The US National Highway Traffic Safety Administration (NHTSA) has claimed that fleet wide weight reductions 'reduce' fleet safety (Kahane, 2003), but this conclusion is strongly disputed (DRI, 2004; NRC, 2002). An important concern with the NHTSA analysis is that it does not

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42 These values are derived by simulating US vehicles running on the CAFE, NEDC, and Japan 10.15 cycles and comparing their estimated fuel economies. Because car manu-facturers design their vehicles to do well on the cycles on which they will be tested, the US vehicles are likely to do a bit worse on the NEDC and Japan 10.15 cycles than they would have had they been designed for those cycles. This will somewhat exaggerate the estimated differences between the cycles in their effects on fuel economy.

separate the effects of vehicle weight and size. In any case, other factors, e.g., overall vehicle design and safety equipment, driver characteristics, road design, speed limits and alcohol regulation and enforcement play a more significant role in vehicle safety than does average weight.

Some have argued that increases in driving associated with reduced fuel cost per mile will nullify the benefits of fuel economy regulations. Increased driving 'is' likely, but it will be modest and decline with higher income and increased motorization. Recent data implies that a driving 'rebound' would reduce the GHG reduction (and reduce oil consumption) benefits from higher standards by about 10% in the United States (Small and Van Dender, 2007) but more than this in less wealthy and less motorized countries.

In deciding to institute a new fuel economy standard, governments should consider the following:
*   Basing stringency decisions on existing standards elsewhere requires careful consideration of differences between the home market and compared markets in fuel quality and availability; fuel economy testing methods; types and sizes of vehicles sold; road conditions that may affect the robustness of key technologies; and conditions that may affect the availability of technologies, for example, availability of sophisticated repair facilities.
*   There are a number of different approaches to selecting stringency levels for new standards. Japan selected its weight class standards by examining 'top runners' – exemplary vehicles in each weight class that could serve as viable targets for future fleet wide improvements. Another approach is to examine the costs and fuel saving effects of packages of available technologies on several typical vehicles, applying the results to the new vehicle fleet (NRC, 2002). Other analyses have derived cost curves (percent increase in fuel economy compared with technology cost) for available technology and applied these to corporate or national fleets (Plotkin *et al.*, 2002). These approaches are not technology-forcing, since they focus on technologies that have already entered the fleet in mass-market form. More ambitious standards could demand the introduction of emerging technologies. Selection of the appropriate level of stringency depends, of course, on national goals and concerns. Further, the selection of enforcement deadlines should account for limitations on the speed with which vehicle manufacturers can redesign multiple models and introduce the new models on a schedule that avoids severe economic disruption.
*   The structure of the standard is as important as its level of stringency. Basing target fuel economy on vehicle weight (Japan, China) or engine size (Taiwan, South Korea) will tend to even out the degree of difficulty the standards impose on competing automakers, but will reduce the potential fuel economy gains that can be expected (because weight-based standards eliminate weight reduction and engine-size-based standards eliminate engine downsizing as viable means of

achieving the standards). Basing the standard on vehicle wheelbase times track width may provide safety benefits by providing a positive incentive to maintain or increase these attributes. Using a uniform standard for all vehicles or for large classes of vehicles (as in the US) is simple and easy to explain, but creates quite different challenges on different manufacturers depending on the market segments they focus on.
*   Allowing trading of fuel economy 'credits' among different vehicles or vehicle categories in an automaker's fleet, or even among competing automakers, will reduce the overall cost of standards without reducing the total societal benefits, but may incur political costs from accusations of allowing companies or individuals to 'buy their way out' of efficiency requirements.
*   Alternatives (or additions) to standards are worth investigating. For example, 'feebates', which award cash rebates to new vehicles whose fuel economy is above a designated level (often the fleet average) and charge a fee to vehicles with lower fuel economy, may be an effective market-based measure to increase fleet fuel economy. An important advantage of feebates is that they provide a 'continuous' incentive to improve fuel economy, because an automaker can always gain a market advantage by introducing vehicles that are more efficient than the current average.

5.5.1.5   *Transport Demand Management*

Transport Demand Management (TDM) is a formal designation for programmes in many countries that improve performance of roads by reducing traffic volumes (Litman, 2003). There are many potential TDM strategies in these programmes with a variety of impacts. Some improve transport diversity (the travel options available to users). Others provide incentives for users to reduce driving, changing the frequency, mode, destination, route or timing of their travel. Some reduce the need for physical travel through mobility substitutes or more efficient land use. Some involve policy reforms to correct current distortions in transport planning practices. TDM is particularly appropriate in developing country cities, because of its low costs, multiple benefits and potential to redirect the motorization process. In many cases, effective TDM during early stages of development can avoid problems that would result if communities become too automobile dependent. This can help support a developing country's economic, social and environmental objectives (Gwilliam *et al.*, 2004).

The set of strategies to be implemented will vary depending on each country's demographic, geographic and political conditions. TDM strategies can have cumulative and synergetic impacts, so it is important to evaluate a set of TDM programmes as a package, rather than as an individual programme. Effective strategies usually include a combination of positive incentives to use alternative modes ('carrots' or 'sweeteners') and negative incentives to discourage driving ('sticks' or 'levellers'). Recent

literature gives a comprehensive overview of these programmes with several case studies (May *et al*., 2003; Litman, 2003; WCTRS and IPTS, 2004). Some major strategies such as pricing and land-use planning are addressed above. Below is a selective review of additional TDM strategies with significant potential to reduce vehicle travel and GHGs.

Employer travel reduction strategies gained prominence from a late 1980s regulation in southern California that required employers with 100 or more employees to adopt incentives and rules to reduce the number of car trips by employees commuting to work (Giuliano *et al*., 1993). The State of Washington in the USA kept a state law requiring travel plans in its most urban areas for employers with 100 or more staff. The law reduced the percentage of employees in the targeted organizations who drove to work from 72–68% and affected about 12% of all trips made in the area. In the Netherlands, the reduction in single occupant commute trips from a travel plan averaged 5–15%. In the UK, in very broad terms, the average effectiveness of UK travel plans might be 6% in trips by drive alone to work and 0.74% in the total vehicle-km travelled to work by car. The overall effectiveness was critically dependent on both individual effectiveness and levels of plan take-up (Rye, 2002).

Parking supply for employees is so expensive that employers naturally have an incentive to reduce parking demand. The literature found the price elasticity of parking demand for commuting at –0.31 to –0.58 (Deuker *et al*., 1998) and –0.3 (Veca and Kuzmyak, 2005) based on a non-zero initial parking price. The State of California enacted legislation that required employers with 50 or more persons who provided parking subsidies to offer employees the option to choose cash in lieu of a leased parking space, in a so-called parking cash-out programme. In eight case studies of employers who complied with the cash-out programme, the solo driver share fell from 76% before cashing out to 63% after cashing out, leading to the reduction in vehicle-km for commuting by 12%. If all the commuters who park free in easily cashed-out parking spaces were offered the cash option in the USA, it would reduce vehicle-km travelled per year by 6.3 billion (Shoup, 1997).

Reducing car travel or CO_2 emissions by substituting telecommuting for actual commuting has often been cited in the literature, but the empirical results are limited. In the USA, a micro-scale study estimated that 1.5% of the total workforce telecommuted on any day, eliminating at most 1% of total household vehicle-km travelled (Mokhtarian, 1998), while a macro-scale study suggested that telecommuting reduced annual vehicle-km by 0–2% (Choo *et al*., 2005).

Reduction of CO_2 emissions by hard measures, such as car restraint, often faces public opposition even when the proposed measures prove effective. Soft measures, such as a provision of information and use of communication strategies and educational techniques (OECD, 2004a) can be used for supporting the promotion of hard measures. Soft measures can also be directly

helpful in encouraging a change in personal behaviour leading to an efficient driving style and reduction in the use of the car (Jones, 2004). Well organized soft measures were found to be effective for reducing car travel while maintaining a low cost. Following travel awareness campaigns in the UK, the concept of Individualized marketing, a programme based on a targeted, personalized, customized marketing approach, was developed and applied in several cities for reducing the use of the car. The programme reduced car trips by 14% in an Australian city, 12% in a German city and 13% in a Swedish city. The Travel Blending technique was a similar programme based on four special kits for giving travel-feedback to the participants. This programme reduced vehicle-km travelled by 11% in an Australian city. The monitoring study after the programme implementation in Australian cities also showed that the reduction in car travel was maintained (Brog *et al*., 2004; Taylor and Ampt, 2003). Japanese cases of travel-feedback programmes supported the effectiveness of soft measures for reducing car travel. The summary of the travel-feedback programmes in residential areas, workplaces and schools indicated that car use was reduced by 12% and CO_2 emissions by 19%. It also implied that the travel-feedback programmes with a behavioural plan requiring a participant to make a plan for a change showed better results than programmes without one (Fujii and Taniguchi, 2005).

5.5.2   Aviation and shipping

In order to reduce emissions from air and marine transport resulting from the combustion of bunker fuels, new policy frameworks need to be developed. Both the ICAO and IMO have studied options for limiting GHG emissions. However, neither has as yet been able to devise a suitable framework for implementing effective mitigation policies.

5.5.2.1   *Aviation*

IPCC (1999), ICAO/FESG (2004a,b), Wit *et al*. (2002 and 2005), Cames and Deuber (2004), Arthur Andersen (2001) and others have examined potential economic instruments for mitigating climate effects from aviation.

At the global level no support exists for the introduction of kerosene taxes. The ICAO policy on exemption of aviation fuel from taxation has been called into question mainly in European states that impose taxes on fuel used by other transport modes and other sources of GHGs. A study by Resource Analysis (1999) shows that introducing a charge or tax on aviation fuel at a 'regional' level for international flights would give rise to considerable distortions in competition and may need amendment of bilateral air service agreements. In addition, the effectiveness of a kerosene tax imposed on a regional scale would be reduced as airlines could take 'untaxed' fuel onboard into the taxed area (the so-called tankering effect).

Wit and Dings (2002) analyzed the economic and environmental impacts of en-route emission charges for all

flights in European airspace. Using a scenario-based approach and an assumed charge level of 50 US$/t$CO_2$, the study found a cut in forecast aviation CO_2 emissions in EU airspace of about 11 Mt (9%) in 2010. This result would accrue partly (50%) from technical and operational measures by airlines and partly from reduced air transport demand. The study found also that an en-route emission charge in European airspace designed in a non-discriminatory manner would have no significant impact on competition between European and non-European carriers.

In a study prepared for CAEP/6, the Forecasting and Economic Analysis Support Group (ICAO/FESG, 2004a) considered the potential economic and environmental impacts of various charges and emission trading schemes. For the period 1998–2010, the effects of a global CO_2 charge with a levy equivalent to 0.02 US$/kg to 0.50 US$/kg jet fuel show a reduction in global CO_2 emissions of 1–18%. This effect is mainly caused by demand effects (75%). The AERO modelling system was used to conduct the analyses (Pulles, 2002).

As part of the analysis of open emission trading systems for CAEP/6, an impact assessment was made of different emission trading systems identified in ICF *et al.* (2004). The ICAO/FESG report (2004b) showed that under a Cap-and-Trade system for aviation, total air transport demand will be reduced by about 1% compared to a base case scenario (FESG2010). In this calculation, a 2010 target of 95% of the 1990-level was assumed for aviation on routes from and to Annex-I countries and the more developed non-Annex-I countries such as China, Hong Kong, Thailand, Singapore, Korea and Brazil. Furthermore a permit price of 20 US$/t$CO_2$ was assumed. Given the relative high abatement costs in the aviation sector, this scenario would imply that the aviation sector would buy permits from other sectors for about 3.3 billion US$.

In view of the difficulty of reaching global consensus on mitigation policies to reduce GHG emissions from international aviation, the European Commission decided to prepare climate policies for aviation. On 20 December 2006 the European Commission presented a legislative proposal that brings aviation emissions into the existing EU Emissions Trading Scheme (EU ETS). The proposed directive will cover emissions from flights within the EU from 2011 and all flights to and from EU airports from 2012. Both EU and foreign aircraft operators would be covered. The environmental impact of the proposal may be significant because aviation emissions, which are currently growing rapidly, will be capped at their average level in 2004–2006. By 2020 it is estimated by model analysis that a total of 183 MtCO_2 will be reduced per year on the flights covered, a 46% reduction compared with business-as-usual. However, aviation reduces the bulk of this amount through purchasing allowances from other sectors and through additional supply of Joint Implementation and Clean Development Mechanism credits. In 2020 aviation reduces its own emissions by 3% below business-as-usual (EC, 2006).

If emission trading or emission charges were applied to the aviation sector in isolation, the two instruments would in principle be equivalent in terms of cost-effectiveness. However, combining the reduction target for aviation with the emission trading scheme of other sectors increases overall economic efficiency by allowing the same amount of reductions to be made at a lower overall cost to society. Therefore, if aviation were to achieve the same environmental goal under emission trading and emission charges, the economic costs for the sector and for the economy as a whole would be lower if this was done under an emission trading scheme including other sectors rather than under a charging system for aviation only.

Alternative policy instruments that may be considered are voluntary measures or fuel taxation for domestic flights. Fuel for domestic flights, which are less vulnerable to economic distortions, is already taxed in countries such as the USA, Japan, India and the Netherlands. In parallel to the introduction of economic instruments such as emission trading, governments could improve air traffic management.

Policies to address the full climate impact of aviation

A major difficulty in developing a mitigation policy for the climate impacts of aviation is how to cover non-CO_2 climate impacts, such as the emission of nitrogen oxides (NO_x) and the formation of condensation trails and cirrus clouds (see also Box 5.1 in section 5.2). IPCC (1999) estimated these effects to be about 2 to 4 times greater than those of CO_2 alone, even without considering the potential impact of cirrus cloud enhancement. This means that the perceived environmental effectiveness of any mitigation policy will depend on the extent to which these non-CO_2 climate effects are also taken into account.

Different approaches may be considered to account for non-CO_2 climate impacts from aviation (Wit et al., 2005). A first possible approach is where initially only CO_2 from aviation is included in for example an emission trading system, but flanking instruments are implemented in parallel such as differentiation of airport charges according to NO_x emissions.

Another possible approach is, in case of emission trading for aviation, a requirement to surrender a number of emission permits corresponding to its CO_2 emissions multiplied by a precautionary average factor reflecting the climate impacts of non-CO_2 impacts. It should be emphasised that the metric that is a suitable candidate for incorporating the non-CO_2 climate impacts of aviation in a single metric that can be used as a multiplier requires further development, being fairly theoretical at present. The feasibility of arriving at operational methodologies for addressing the full climate impact of aviation depends not only on improving scientific understanding of non-CO_2 impacts, but also on the potential for measuring or calculating these impacts on individual flights.

5.5.2.2   Shipping

CO$_2$ emission indexing scheme

The International Maritime Organisation (IMO), a specialized UN agency, has adopted a strategy with regard to policies and measures, focusing mainly on further development of a CO$_2$ emission indexing scheme for ships and further evaluation of technical, operational and market-based solutions.

The basic idea behind a CO$_2$ emission index is that it describes the CO$_2$ efficiency (i.e., the fuel efficiency) of a ship, i.e., the CO$_2$ emission per tonne cargo per nautical mile. This index could, in the future, assess both the technical features (e.g., hull design) and operational features of the ship (e.g., speed).

In June 2005, at the 53rd session of the Marine Environment Protection Committee of IMO (IMO, 2005), interim guidelines for voluntary ship CO$_2$ emission indexing for use in trials were approved. The Interim Guidelines should be used to establish a common approach for trials on voluntary CO$_2$ emission indexing, which enable shipowners to evaluate the performance of their fleet with regard to CO$_2$ emissions. The indexing scheme will also provide useful information on a ship's performance with regard to fuel efficiency and may thus be used for benchmarking purposes. The interim guidelines will later be updated, taking into account experience from new trials as reported by industry, organisations and administrations.

A number of hurdles have to be overcome before such a system could become operational. The main bottleneck appears to be that there is major variation in the fuel efficiency of similar ships, which is not yet well understood (Wit *et al.*, 2004). This is illustrated by research by the German delegation of IMO's Working Group on GHG emission reduction (IMO, 2004), in which the specific energy efficiency (i.e., a CO$_2$ emission index) was calculated for a range of container ships, taking into account engine design factors rather than operational data. The results of this study show that there is considerable scatter in the specific engine efficiency of the ships investigated, which could not be properly explained by the deadweight of the ships, year of build, ship speed and several other ship design characteristics. The paper therefore concludes that the design of any CO$_2$ indexing scheme and its differentiation according to ship type and characteristics, requires in-depth investigation. Before such a system can be used in an incentive scheme, the reasons for the data scatter need to be understood. This is a prerequisite for reliable prediction of the economic, competitive and environmental effects of any incentive based on this method.

Voluntary use and reporting results of CO$_2$ emission indexing may not directly result in GHG emission reductions, although it may well raise awareness and trigger certain initial moves towards 'self regulation'. It might also be a first step in the process of designing and implementing some of the other policy options. Reporting of the results of CO$_2$ emission indexing could thus generate a significant impetus to the further development and implementation of this index, since it would lead to widespread experience with the CO$_2$ indexing methodology, including reporting procedure and monitoring, for shipping companies as well as for administrations of states.

In the longer term, in order to be more effective, governments may consider using CO$_2$ indexing via the following paths:
1. The indexing of ship operational performance is introduced as a voluntary measure and over time developed and adopted as a standard;
2. Based on the experience with the standard, it will act as a new functional requirement when new buildings are ordered, hence over time the operational index will affect the requirements from ship owners related to the energy efficiency of new ships;
3. Differentiation of en route emission charges or existing port dues on the basis of a CO$_2$ index performance;
4. To use the CO$_2$ index of specific ship categories as a baseline in a (voluntary) baseline-and-credit programme.

Economic instruments for international shipping

There are currently only a few cases of countries or ports introducing economic instruments to create incentives to reduce shipping emissions. Examples include environmentally differentiated fairway dues in Sweden, the Green Award scheme[43] in place in 35 ports around the world, the Green Shipping bonus in Hamburg and environmental differentiation of tonnage tax in Norway. None of these incentives are based on GHG emissions, but generally relate to fuel sulphur content, engine emissions (mainly NO$_x$), ship safety features and management quality.

Harrison *et al.* (2004) explored the feasibility of a broad range of market-based approaches to regulate atmospheric emissions from seagoing ship in EU sea areas. The study focused primarily on policies to reduce the air pollutants SO$_2$ and NO$_x$, but the approaches adopted may to a certain extent also be applicable to other emissions, including CO$_2$. According to a follow-up study by Harrison *et al.* (2005) the main obstacles to a programme of voluntary port dues differentiation are to provide an adequate level of incentive, alleviating ports' competitive concerns and reconciling differentiation with specially negotiated charges. Swedish experience suggests that when combined with a centrally determined mandatory charging programme, these problems may be surmountable. However, in many cases a voluntary system would not likely be viable and other approaches to emissions reductions may therefore be required.

An alternative economic instrument, such as a fuel tax is vulnerable to evasion; that is ships may avoid the tax by taking

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fuel on board outside the taxed area. Offshore bunker supply is already common practice to avoid paying port fees or being constrained by loading limits in ports. Thus even a global fuel tax could be hard to implement to avoid evasion, as an authority at the port state level would have to collect the tax (ECON, 2003). A CO_2-based route charge or a (global) sectoral emission trading scheme would overcome this problem if monitoring is based on the carbon content of actual fuel consumption on a single journey. As yet there is no international literature that analyzes the latter two policy options. Governments may therefore consider investigating the feasibility and effectiveness of emission charges and emission trading as policy instruments to reduce GHG emissions from international shipping.

5.5.3   Non-climate policies

Climate change is a minor factor in decision making and policy in the transport sector in most countries. Policies and measures are often primarily intended to achieve energy security and/or sustainable development benefits that include improvements in air pollution, congestion, access to transport facilities and recovery of expenditure on infrastructure development. Achieving GHG reduction is therefore often seen as a co-benefit of policies and measures intended for sustainable transport in the countries. On the other hand, there are many transport policies that lead to an increase in GHG emissions. Depending on their orientation, transport subsidies can do both.

The impact of transport subsidies

Globally, transport subsidies are significant in economic terms. Van Beers and Van den Bergh (2001) estimated that in the mid-1990s transport subsidies amounted to 225 billion US$, or approximately 0.85% of the world GDP. They estimated that transport subsidies affect over 40% of world trade. In a competitive environment (not necessarily under full competition), subsidies decrease the price of transport. This results in the use of transport above its equilibrium value and most of the time also results in higher emissions, although this depends on the type of subsidy. Secondly, they decrease the incentive to economise on fuel, either by driving efficiently or by buying a fuel-efficient vehicle.

A quantitative appraisal of the effect of subsidies on GHG emissions is very complicated (Nash et al., 2002). Not only have shifts between fuels and transport modes to be taken into account, but the relation between transport and the production structure also needs to be analysed. As a result, reliable quantitative assessments are almost non-existent (OECD, 2004a). Qualitative appraisals are less problematic. Transport subsidies that definitely raise the level of GHG emissions include subsidies on fossil transport fuels, subsidies on commuting and subsidies on infrastructure investments.

Many, mostly oil producing, countries provide their inhabitants with transport fuels below the world price. Some

countries spend more than 4% of their GDP on transport fuel subsidies (Esfahani, 2001). Many European countries and Japan have special fiscal arrangements for commuting expenses. In most of these countries, taxpayers can deduct real expenses or a fixed sum from their income (Bach, 2003). By reducing the incentive to move closer to work, these tax schemes enhance transport use and emissions.

Not all transport subsidies result in higher emissions of GHGs. Some subsidies stimulate the use of climate-friendly fuels. In many countries, excise duty exemptions on compressed natural or petroleum gas and on biofuels exist (e.g., Riedy, 2003). If these subsidies result in a change in the fuel mix, without resulting in more transport movements, they may actually decrease emissions of GHGs.

The most heavily subsidised form of transport is probably public transport, notably suburban and regional passenger rail services. In the USA, fares only cover 25% of the costs, in Europe 50% (Brueckner, 2004). Although public transport generally emits fewer GHGs per passenger-km, the net effect of these subsidies has not been quantified. It depends on the balance between increased GHG emissions due to higher demand (due to lower 'subsidised' fares) and substitution of relatively less efficient transport modes.

5.5.4   Co-benefits and ancillary benefits

The literature uses the term ancillary benefits when focusing primarily on one policy area, and recognizing there may be benefits with regard to other policy objectives. One speaks of co-benefits when looking from an integrated perspective. This section focuses on co-benefits and ancillary benefits of transport policies. Chapter 11.6 provides a general discussion of the benefits and linkages related to air pollution policies.

As mentioned above, several different benefits can result from one particular policy. In the field of transport, local air pollutants and GHGs have a common source in motorized traffic, which may also induce congestion, noise and accidents. Addressing these problems simultaneously, if possible, offers the potential of large cost reductions, as well as reductions of health and ecosystems risks. A recent review of costs of road transport emissions, and particularly of particulates PM2.5, for European countries strongly supports that view (HEATCO, 2006). Tackling these problems would also contribute to more effective planning of transport, land use and environmental policy (UN, 2002; Stead et al., 2004). This suggests that it would be worthwhile to direct some research towards the linkages between these effects.

Model studies indicate a potential saving of up to 40% of European air pollution control costs if the changes in the energy systems that are necessary for compliance with the Kyoto protocol were simultaneously implemented (Syri et al., 2001). For China, the costs of a 5–10% CO_2 reduction
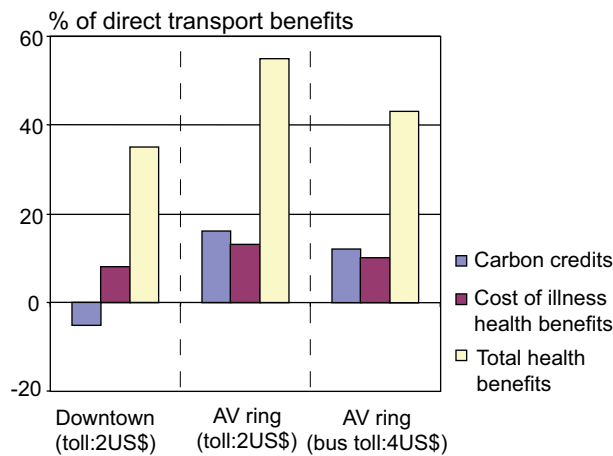
% of direct transport benefits

Figure 5.19: *Co-benefits from different mitigation measures in Santiago de Chile*
Note: toll is applied for cars/busses to enter downtown area or inside the Americo Vespucio ring around the city.
Source: Cifuentes and Jorquera, 2002.

would be compensated by increased health benefits from the accompanying reduction in particulate matter (Aunan *et al.*, 1998). McKinley *et al.* (2003) analyzed several integrated environmental strategies for Mexico City. They conclude that measures to improve the efficiency of transport are the key to joint local/global air pollution control in Mexico City. The three measures in this category that were analyzed, taxi fleet renovation, metro expansion and hybrid buses, all have monetized public health benefits that are larger than their costs when the appropriate time horizon is considered.

A simulation of freight traffic over the Belgian network indicated that a policy of internalizing the marginal social costs caused by freight transport types would induce a change in the modal shares of trucking, rail and inland waterways transport. Trucking would decrease by 26% and the congestion cost it created by 44%. It was estimated that the total cost of pollution and GHG emissions (together) would decrease by 15.4%, the losses from accidents diminish by 24%, the cost of noise by 20% and wear and tear by 27%. At the same time, the total energy consumption by the three modes would decrease by 21% (Beuthe *et al.*, 2002).

Other examples of worthwhile policies can be given. The policy of increasing trucks' weight and best practices awareness in Sweden, UK and the Netherlands lead to a consolidation of loads that resulted in economic benefits as well as environmental benefits, including a decrease in CO_2 emissions (MacKinnon, 2005; Leonardi and Baumgartner, 2004). Likewise, the Swiss heavy vehicle fee policy also leads to better loaded vehicles and a decrease of 7% in CO_2 emissions (ARE, 2004a).

Obviously, promotion of non-motorized transport (NMT) has the large and consistent co-benefits of GHG reduction, air quality and people health improvement (Mohan and Tiwari, 1999).

In the City of London a congestion charge was introduced in February 2003, to reduce congestion. Simultaneous with the introduction of the charge, investment in public transport increased to provide a good alternative. The charge is a fee for motorists driving into the central London area. It was introduced in February 2003. Initially set at 5 £/day (Monday to Friday, between 7 am and 6.30 pm), it was raised to 8 £ in July 2005. The charge will be extended to a larger area in 2007. On a cost-benefit rating, the results of the charge are not altogether clear (Prud'homme and Bocarejo, 2005, Mackie, 2005). However, it contributed to a 30% decrease of the traffic by the chargeable vehicles in the area and less congestion, to higher speed of private vehicles (+20%) and buses (+7%), and to an increased use of public transport, plus more walking and bicycling. The charge has had substantial ancillary benefits with respect to air quality and climate policy. All the volume and substitution effects in the charging zone has led to an estimated reductions in CO_2 emissions of 20%. Primary emissions of NO_x and PM10 fell by 16% after one year of introduction (Transport for London, 2006). A variant of that scheme has been in operation since 1975 in Singapore with similar results; Stockholm is presently experimenting with such a system, Trondheim, Oslo and Durham are other examples.

Under the Integrated Environmental Strategies Program of the US EPA, analysis of public health and environmental benefits of integrated strategies for GHG mitigation and local environmental improvement is supported and promoted in developing countries. A mix of measures for Chile has been proposed, aimed primarily at local air pollution abatement and energy saving. Measures in the transport sector (CNG buses, hybrid diesel-electric buses and taxi renovation) proved to provide little ancillary benefits in the field of climate policy, see Figure 5.19. Only congestion charges were expected to have substantial ancillary benefits for GHG reduction (Cifuentes *et al.*, 2001, Cifuentes & Jorquera, 2002).

While there are many synergies in emission controls for air pollution and climate change, there are also trade-offs. Diesel engines are generally more fuel-efficient than gasoline engines and thus have lower CO_2 emissions, but increase particle emissions. Air quality driven measures, like obligatory particle matter (PM) and NO_x filters and in-engine measures, do not result in higher fuel use if appropriate technologies are used, like Selective Catalytic Reduction (SCR)- NO_x catalyst.

5.5.5 Sustainable Development impacts of mitigation options and considerations on the link of adaptation with mitigation.

Within the transport sector there are five mitigation options with a clear link between sustainable development, adaptation and mitigation. These areas are biofuels, energy efficient, public transport, non-motorised transport and urban planning. Implementing these options would generally have positive social, environmental and economic side effects. The economic

effects of using bio-energy and encouraging public transport systems, however, need to be evaluated on a case-by-case basis. For transport there are no obvious links between mitigation and adaptation policies and the impact on GHG emissions due to adaptation is expected to be negligible.

Mitigation and sustainable development is discussed from a much wider perspective, including the other sectors, in Chapter 12, Section 12.2.4.

5.6 Key uncertainties and gaps in knowledge

Key uncertainties in assessment of mitigation potential in the transport sector through the year 2030 are:
- World oil supply and its impact on prices and alternative transport fuels;
- R&D outcomes in several areas, especially biomass fuel production technology and its sustainability if used on a massive scale, and batteries. These outcomes will strongly influence the future costs and performance of a wide range of transport technologies.

The degree to which the potential can be realized will crucially depend on the priority that developed and developing countries give to GHG emissions mitigation.

A key gap in knowledge is the lack of comprehensive and consistent assessments of the worldwide potential and cost to mitigate transport's GHG emissions. There are also important gaps in basic statistics and information on transport energy consumption and GHG mitigation, especially in developing countries.

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