



International
Energy Agency

TRANSPORT, ENERGY AND CO₂

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**Moving Toward
Sustainability**



TRANSPORT, ENERGY AND CO₂

Moving Toward Sustainability

Transport accounts for nearly one-quarter of global energy-related CO₂ emissions. To achieve the necessary deep cuts in greenhouse gas emissions by 2050, transport must play a significant role.

However, without strong global action, car ownership worldwide is set to triple to over two billion by 2050. Trucking activity will double and air travel could increase four-fold. These trends will lead to a doubling of transport energy use, with an even higher growth rate in CO₂ emissions as the planet shifts toward high-CO₂ synthetic fuels. How can we enable mobility without accelerating climate change?

Transport, Energy and CO₂: Moving Toward Sustainability provides answers to this question. It finds that if we change the way we travel, adopt technologies to improve vehicle efficiency and shift to low-CO₂ fuels, we can move onto a different pathway where transport CO₂ emissions by 2050 are far below current levels, at costs that are lower than many assume. The report discusses the prospects for shifting more travel to the most efficient modes and reducing travel growth rates, improving vehicle fuel efficiency by up to 50% using cost-effective, incremental technologies, and moving toward electricity, hydrogen, and advanced biofuels to achieve a more secure and sustainable transport future. If governments implement strong policies to achieve this scenario, transport can play its role and dramatically reduce CO₂ emissions by 2050.

This publication is one of three new IEA end-use studies, together with industry and buildings, which look at the role of technologies and policies in transforming the way energy is used in these sectors.

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The International Energy Agency (IEA) is an autonomous body which was established in November 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme.

It carries out a comprehensive programme of energy co-operation among twenty-eight of the thirty OECD member countries. The basic aims of the IEA are:

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- To operate a permanent information system on international oil markets.
- To provide data on other aspects of international energy markets.
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 - To promote international collaboration on energy technology.
 - To assist in the integration of environmental and energy policies, including relating to climate change.



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FOREWORD

About 25% of worldwide CO₂ emissions are attributable to transport. Though cars and trucks represent the bulk of these emissions (about 75% worldwide), aviation and shipping emissions are growing rapidly. While energy use in transport could double by 2050, associated CO₂ emissions must be cut dramatically as part of an overall strategy to cut energy-related CO₂ emissions by 50%.

The first priority should be to adopt technologies and practices that are cost-effective today. This will lead to substantial gains in vehicle fuel economy – we target a 50% improvement by 2030 for new light-duty vehicles. Relatively low-cost opportunities may be available in terms of vehicle electrification, such as via plug-in hybrids. We should also move strongly toward better urban development practices and encourage sensible changes in the way we travel, by investing in a new generation of urban and inter-city transit systems.

Yet such savings will only be sufficient to slow the growth in vehicle travel and stabilise the growth in CO₂. A revolution in technology will be needed to move toward a truly low CO₂ future. This will be built on some combination of electricity, hydrogen and biofuels. Important hurdles exist to reach substantial use of any of these fuels, including infrastructure requirements, costs and – especially in the case of biofuels – the need for a pathway toward the use of truly sustainable feedstocks. But through a combination of RD&D, careful and co-ordinated planning, deployment, and learning by doing, the ambitious long-term targets described in this report can be achieved.

Bringing about this technology transition will not be easy. It will require both a step-change in policy implementation by governments, and unprecedented investment in new technologies and supporting infrastructure such as electricity recharging systems. Countries will need to work together, and with a range of stakeholders, to ensure everyone moves in the same direction. Moreover, since the vast majority of growth in travel, energy use and CO₂ will occur in non-OECD countries, these countries will need to be part of the solution. But they will also share in the very important benefits that a sustainable, low-CO₂ transport future can provide.

This publication has been produced under my authority as Executive Director of the International Energy Agency (IEA). The views expressed do not necessarily reflect the views or policies of individual IEA member countries.

Nobuo Tanaka
Executive Director

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Lew Fulton was the project leader and had overall responsibility for the design and development of the study. The other main authors were Pierpaolo Cazzola, François Cuenot, Kazunori Kojima, Takao Onoda, John Staub and Michael Taylor from the IEA. Philippe Crist from OECD/ITF led the analysis for shipping and Alan McKinnon, assisted by Maja Piecyk, from the Heriot-Watt University Edinburgh for freight transport. The work also benefited from the expertise of many other IEA colleagues, in particular Cecilia Tam, Timur Gül, Paul Dowling, Anselm Eisentraut and Soufien Taamallah.

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Kamala Ernest, Programme Officer - Transport, United Nations Environment Programme

John Ernst, Vice Director, Southeast Asia & Monitoring and Evaluation, Institute for Transportation and Development Policy

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Karl Fjellstrom, Vice Director, China, Institute for Transportation and Development Policy

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Francoise Nemry, Scientific Officer, Institute for Perspective Technological Studies, Joint Research Centre of the European Commission

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Steven Plotkin, Argonne National Laboratory, United States

Mary Preville, Acting Director General, Office of Energy R&D, Natural Resources Canada

Sophie Punte, Executive Director, Clean Air Initiative-Asia Center

Eugene Reiser, Operations Research Analyst, Energy Information Administration, Department of Energy of the United States

Michael Replogle, President, Environmental Defense

John A. Rogers, Energy Efficiency and Climate Change, World Bank

Lee Schipper, Project Scientist, Global Metropolitan Studies, University of California Berkeley, United States

Rolf Schmitz, Head of Energy Research Section, Federal Department of the Environment, Transport, Energy and Communications, Swiss Federal Office of Energy

Bradley Schroeder, Project Manager, BikeTown Africa, Institute for Transportation and Development Policy

Philippe Schulz, Energy & Environment Senior Manager, Renault

Helga Stenseth, Energy Adviser, Norwegian Delegation to the Organisation for Economic Co-operation and Development

Marek Sturc, Policy Officer, Climate Change & Air Directorate, Directorate General Environment, European Commission

Martijn van Walwijk, Independent consultant on automotive fuels and drivetrains and Secretary, IEA Hybrid & Electric Vehicle Implementing Agreement

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Comments and questions are welcome and should be addressed to:

Transport Analysts
Directorate of Sustainable Policy and Technology
International Energy Agency
9, rue de la Fédération
75739 Paris Cedex 15
France

Email: transportinfo@iea.org

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EXECUTIVE SUMMARY

Overview

Transport accounts for about 19% of global energy use and 23% of energy-related carbon dioxide (CO₂) emissions and these shares will likely rise in the future. Given current trends, transport energy use and CO₂ emissions are projected to increase by nearly 50% by 2030 and more than 80% by 2050.

This future is not sustainable. The Intergovernmental Panel on Climate Change (IPCC) advises that, to avoid the worst impacts from climate change, global CO₂ emissions must be cut by at least 50% by 2050. To achieve this, transport will have to play a significant role. Even with deep cuts in CO₂ from all other energy sectors, if transport does not reduce CO₂ emissions well below current levels by 2050, it will be very difficult to meet targets such as stabilising the concentration of greenhouse gas (GHG) emissions in the atmosphere at a level of 450 ppm of CO₂ equivalent.

Substantially changing transport trends will require both the widespread adoption of current best available technology, and the longer-term development and deployment of a range of new technologies. It will also require strong policies to ensure rapid uptake and full utilisation of these technologies, and to encourage sensible changes in travel patterns. It will involve industry, governments and consumers. This book shows a clear pathway for achieving a low CO₂, sustainable transport future.

All transport modes will need to reduce their emissions significantly compared to the Baseline trends, in every region of the world. This publication shows how the introduction and widespread adoption of new vehicle technologies and fuels, along with some shifting in passenger and freight transport to more efficient modes, can result in a 40% reduction in CO₂ emissions below 2005 levels. As outlined in the IEA publication *Energy Technology Perspectives 2008* (ETP 2008), such emission reductions in transport can be consistent with a goal to reduce total global energy-related CO₂ emissions in 2050 by 50% from current levels, since greater emission reductions are possible in some other sectors. Further, much of the transport CO₂ reductions can probably be achieved at a low overall cost to society, with costs for advanced technologies reducing over time, as a result of learning from increasing production and use. However to achieve the targets, marginal costs up to USD 200 per tonne of CO₂ saved, or even higher, may be unavoidable.

The benefits of strong decarbonisation in transport also extend to energy security. Transport oil use can be cut by more than half in 2050 compared to today's level, vastly increasing the likely stability and security of supplies. Energy carriers such as hydrogen (H₂) and electricity also have far better energy security characteristics, since they can be produced from a wide range of primary energy sources rather than just oil. Additionally, in many cases a significant fraction of these primary energy sources can be obtained within the countries and regions that consume them.

A sustainable pathway for transport

Current and emerging technologies have the potential to deliver substantial reductions in CO₂ emissions from transport. But they need to be introduced rapidly, at a rate and on a scale that is unprecedented in the last 40 years of transport evolution. Which new technologies will ultimately show the most promise is still uncertain, as is the contribution that could be achieved from travel shifts to more efficient modes. This publication therefore uses a number of Baseline and CO₂ abatement scenarios to examine these issues.

Box ES.1 ► Scenarios considered in this study

This analysis uses the same basic set of scenarios originally developed for the ETP 2008 publication. These cover various futures through 2050, including a Baseline and several ways to achieve very low CO₂ emissions for transport. Specific scenarios include:

Baseline: follows the IEA World Energy Outlook 2008 (WEO 2008) Reference Case to 2030 and then extends it to 2050. It reflects current and expected future trends in the absence of new policies.

High Baseline: this scenario considers the possibility of higher growth rates in car ownership, aviation and freight travel over the period to 2050 than occur in the Baseline.

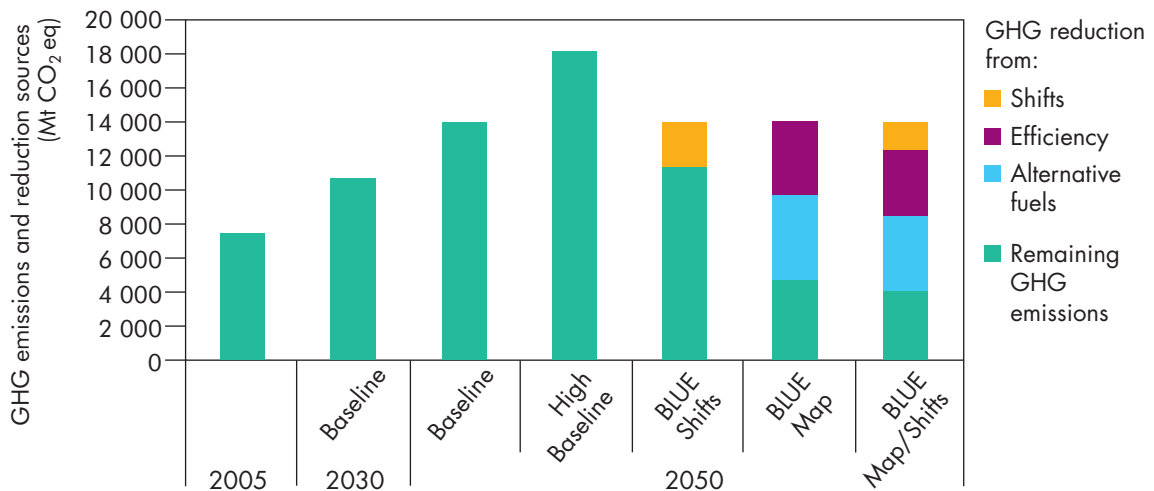
BLUE CO₂ reduction scenarios: these scenarios update those presented in the IEA Energy Technology Perspectives 2008 report. The BLUE variant scenarios are developed based on achieving the maximum CO₂ reduction in transport by 2050 using measures costing up to USD 200 per tonne. These scenarios will require strong policies to be achieved.

- **BLUE Map:** this scenario achieves CO₂ emissions by 2050 that are 30% below 2005 levels. It does this via strong improvements in vehicle efficiency and introduction of advanced technologies and fuels such as plug-in hybrids (PHEVs), electric vehicles (EVs), and fuel cell vehicles (FCVs). It does not envisage significant changes in travel patterns.
- **BLUE EV Success:** Similar to BLUE Map and achieving a similar CO₂ reduction, but with electric and plug-in hybrid vehicles achieving greater cost reductions and better performance to the point where they dominate light-duty vehicle (LDV) sales by 2050, to the exclusion of fuel cell vehicles.
- **BLUE Shifts:** this scenario focuses on the potential of modal shift to cut energy use and CO₂ emissions. Air and LDV travel grow by 25% less than in the Baseline to 2050, and trucking by 50% less. The travel is shifted to more efficient modes and (for passenger travel) to some extent eliminated via better land-use planning, greater use of information technology, and other measures that reduce the need for motorised travel. Compared to the Baseline in 2050, BLUE Shifts results in a 20% reduction in energy use and CO₂.
- **BLUE Map/Shifts:** this scenario combines the BLUE Map and BLUE Shifts scenarios, gaining CO₂ reductions from efficiency improvements, new vehicle and fuel technologies, and modal shift. It results in a 40% reduction in CO₂ below 2005 levels by 2050.

The BLUE Map scenario

The BLUE Map scenario is the “foundation” scenario for this study. It shows that a 30% reduction in transport CO₂ emission in 2050 compared to 2005 can be achieved by the uptake of technologies and alternative fuels across all transport modes that cost less than USD 200 per tonne of CO₂ saved. Under this scenario, improvements in transport energy efficiency offer the largest and least expensive CO₂ reductions, at least over the next ten years. Adoption of advanced vehicle technologies and new fuels also provides important contributions to this scenario, especially after 2020. The impacts in terms of CO₂ reductions in 2050 (along with those for other scenarios) are shown in Figure ES-1.

Figure ES-1 ► Summary of GHG reductions by scenario in this study¹



Key point

Transport sector GHG emissions in BLUE Map/Shifts are 40% below 2005 levels.

Vehicle efficiency improvements in BLUE Map

A principal finding of the BLUE Map analysis is that the implementation of incremental fuel economy technologies could cost-effectively cut the fuel use and CO₂ emissions per kilometre of new light-duty vehicles (LDVs) worldwide by 30% by 2020 and 50% by 2030. Similar efficiency improvements may be possible for other modes, although the estimation of technology potentials for trucks, ships and aircraft is not as accurate as it is for LDVs in this analysis. Further, many of the available improvements for these modes are expected to occur in the Baseline scenario, which includes improvements of 20% to 25% by 2050. But the achievement of a 30% to 50% reduction in fuel use per kilometre travelled for trucks, ships and aircraft by 2050 appears possible. For all modes and types of vehicles, the identification and

1. In this figure, and throughout this study except where noted, greenhouse gases include CO₂ emissions from vehicles, and CO₂, methane and nitrogen oxide emissions from fuel production. It does not include other GHGs, such as water vapour from aircraft or sulphur oxide from shipping.

setting of efficiency targets for the 2020-30 timeframe would be valuable to help stimulate and co-ordinate action, particularly if backed up by the development of policies around the world to help achieve these targets.

A 30% to 50% improvement in new vehicle efficiency across modes by 2030 would help to achieve a stock average improvement of a similar magnitude by 2050. In the BLUE Map scenario, this cuts transport energy use and CO₂ enough to just about stabilise it at 2005 levels. To go well below 2005 levels, switching to new low-CO₂ fuels, along with travel and modal shift policies, will need to play increasingly important roles.

Alternative fuels in BLUE Map

In the Baseline scenario, petroleum-based fuels continue to account for about 90% of all transport fuel in 2050. In the High Baseline, an increasing share of very high CO₂ fuels, such as coal-to-liquids, increases CO₂ emissions even faster than fuel use. In contrast, in the BLUE Map scenario, the share of petroleum and other fossil fuels falls to below 50%. They are replaced by a combination of advanced, low CO₂ biofuels, electricity and hydrogen. If produced from low CO₂ feedstocks, any one of these options might be sufficient to achieve the outcomes envisaged, but each also has drawbacks and may not reach its full potential. A combination of these can maximise the chances of overall success, even if it would result in higher investment costs to develop adequate production and distribution infrastructures. Pursuing a combination, at least in the initial stage, appears to be a wise choice to maximise the potential benefits without locking-out potential solutions.

Ethanol from sugar cane can already provide low-cost biofuels, and increasingly does. Advanced (second-generation) biofuels, such as ligno-cellulosic ethanol and biodiesel derived from biomass (biomass to liquids), appear to have the best long-term potential to provide sustainable, low life-cycle GHG fuels, but more research, development and demonstration (RD&D) will be needed before commercial scale production is likely to occur. For all biofuels, important sustainability questions must be resolved, such as the impact of production on food security and sensitive ecosystems as a result of land-use change. About a 20-fold increase in biofuels is needed to achieve the outcomes envisaged in the BLUE Map scenario by 2050. If done wisely, this should be possible using only a small share of global agricultural land.

Advanced vehicle technologies in BLUE Map

EVs, PHEVs, and FCVs all play an important role in BLUE map, especially after 2020. EVs are rapidly emerging as an important option, especially as lithium-ion battery costs decline. It now appears that batteries for a pure electric vehicle, in high-volume production, might cost as little as USD 500/kWh in the near term, low enough to bring the battery cost for a vehicle with a 150 km range down to about USD 15 000. This is still very expensive. But with savings from removing the internal combustion engine, and with relatively low-cost electricity as the fuel, this might be sufficient to allow EVs to achieve commercial success over the next five to ten years, if coupled with policy assistance such as support for the development of an appropriate recharging infrastructure. The cost of oil, the principal competing fuel,

will also be an important factor. Since the impact of EVs on CO₂ emissions depends on the CO₂ intensity of electricity generation, it would make sense to deploy EVs first in those regions with already low CO₂ generation or a firm commitment to move in that direction. This would include Japan, the European Union, and parts of North and South America.

A potentially important transition step to EVs is offered by PHEVs. By increasing the battery storage in hybrid vehicles and offering a plug-in option, these vehicles represent an important step toward vehicle electrification that builds incrementally on an emerging hybrid vehicle technology. Like hybrids, PHEVs use both engine and motor, which adds cost. But the advantage of PHEVs lies in providing a potentially significant share of driving on electricity with a small, and therefore relatively inexpensive, battery pack. For example, an 8 kWh battery pack might cost USD 5 000 to USD 6 000 in the near term and provide 40 kilometres of driving range on electricity. For many drivers, running most of the first 40 kilometres per day on electricity could cut oil use dramatically, by 50% or more in some cases. PHEVs may also require less new infrastructure than pure EVs since the car is not dependent solely on electricity and has a full driving range on liquid fuel.

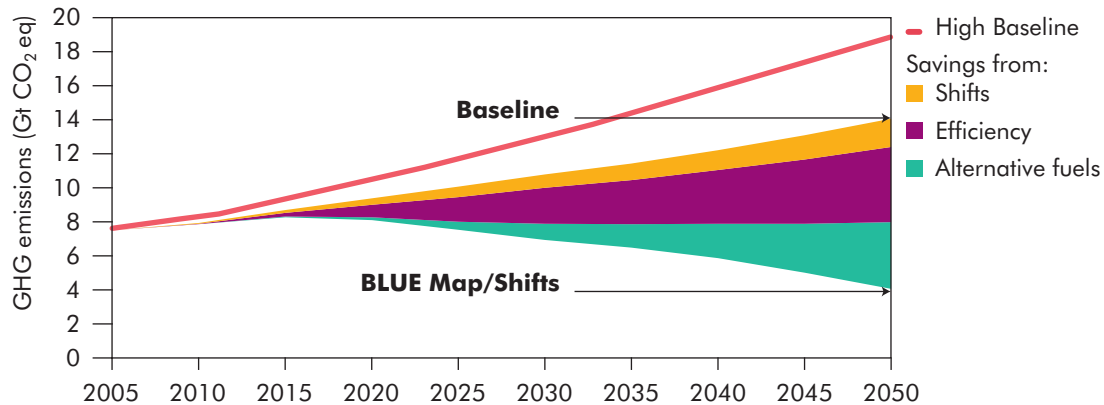
In the BLUE Map scenario, both EVs and PHEVs are initially deployed in 2010 and increase in sales to well over one million per year by 2020. EVs and PHEVs experience rapid market penetration around the world, each reaching annual sales of around 50 million by 2050, primarily as passenger LDVs but also a small share of trucks. The widespread introduction of EVs illustrated in the BLUE Map scenario requires adequate investments and co-ordination amongst governments and industry for the development of recharging infrastructure for EVs. In a separate scenario called BLUE EV Success, in which EVs almost fully dominate LDV sales by 2050 (essentially displacing FCVs), their sales exceed 100 million per year.

Hydrogen fuel cell vehicles also play a key role in the BLUE Map scenario. FCVs co-exist with EVs and are produced commercially beginning around 2020. They reach a significant sales share by 2030, with sales then rising rapidly to nearly 60 million by 2050. Recent cost reductions in fuel cell systems for vehicles increase the likelihood that FCVs can eventually become commercialised, although costs and on-board energy storage are still important concerns. As battery costs drop, hybridising fuel cells appears increasingly attractive, since batteries can help provide peak power to the motor, allow a smaller fuel cell stack to be used, and improve efficiency through regenerative braking. The development of a hydrogen production and distribution infrastructure is necessary, and will require substantial new investments if hydrogen becomes used on a large scale. Like electricity, H₂ must be produced with low CO₂ technologies in order for FCVs to provide significant CO₂ reductions. This will result in higher hydrogen costs than if it were produced from, for example, reforming natural gas.

The BLUE Shifts scenario

Beyond changes to future vehicles and fuels, shifts in some passenger travel and freight transport to more efficient modes can also play an important role in reducing energy use and CO₂ emissions. Certainly from the point of view of cities around the world, developing in a manner that minimises reliance on private motorised travel

Figure ES-2 ▶ Contribution of emissions reduction options in BLUE Map/Shifts Scenario, 2005-50



Key point

A 10 Gt reduction in GHG can be achieved by 2050 via modal shift, efficiency and alternative fuels.

should be a high priority given the strong co-benefits in terms of reduced traffic congestion, lower pollutant emissions and general liveability.

The BLUE Shifts scenario considers one possible future modal mix, in contrast to that implied in the Baseline, mainly in order to illustrate the potential energy and CO₂ reductions that could result.² It envisages an average worldwide reduction in private LDV and aviation passenger travel of 25% by 2050 relative to the Baseline scenario, and up to a 50% reduction compared to the High Baseline scenario (Figure ES-1). In addition, it includes a shift in freight movement to rail transport, which cuts long-haul truck transport growth between 2010 and 2050 by half. By shifting travel and goods transport to advanced bus and rail systems, along with some outright reductions in travel growth due to better land-use planning and improved non-motorised transport infrastructure, along with some telecommunications substitution for travel, about a 20% reduction in energy use appears feasible by 2050 compared to the Baseline, or about a 40% reduction compared to the High Baseline scenario. Even more ambitious mode shifting may be possible, but it will require strong policies and political will.

The BLUE Map/Shifts scenario

Overall, with the efficiency, low-GHG fuels and advanced vehicles, and modal shift taken together, in the BLUE Map/Shifts scenario CO₂ emissions in transport are cut by 40% in 2050 compared to 2005, and by 70% compared to the Baseline in 2050 (Figure ES-2). This represents a 10 gigatonne (Gt) reduction from the 14 Gt that would otherwise be emitted by the transport system in 2050 in the Baseline and a 14 Gt reduction compared to the 18 Gt in the High Baseline. After 2050,

2. This scenario relies on more uncertain information in comparison to other sections of the analysis. It has been developed to provide a basis for estimating the potential energy and CO₂ impacts of modal shifts, and it will be refined further in the future.

further modal shifting and efficiency improvements, and the deeper penetration of low CO₂ alternative fuels, will be needed to keep transport on a downward CO₂ trend.

It will be extremely challenging for transport to achieve the outcomes implicit in the BLUE Map/Shifts scenario. Very strong policies will be needed, both to encourage development and implementation of alternatives, and to encourage consumers and businesses to embrace these alternatives. The following sections outline the contribution from the different modes and the policies that will be needed.

Modal findings and policy considerations

The four most important modes, in terms of their expected contribution to CO₂ in the Baseline scenario in 2050, are LDVs (43%), trucks (21%), aviation (20%) and shipping (8%). In the BLUE Shifts scenario, the role for buses and rail increases significantly and CO₂ reductions via efficiency and alternative fuels in these modes become increasingly important, though they are already quite efficient and likely to become more so.

Light-duty vehicles

Car, sport utility vehicle (SUV) and passenger light-truck ownership around the world is expected to rise mainly as a function of income. In the Baseline scenario, the total stock increases from about 700 million in 2005 to nearly 2 billion by 2050. In the High Baseline scenario, car ownership rates rise even faster (with ownership more closely tracking the historical rates observed in the OECD Europe and Japan for a given income level), and reach nearly 3 billion. One obvious impact of this growth is a similar increase in the rate of fuel use, unless vehicles become far more efficient than they are today. Modal shifts to mass transit, walking and cycling, as well as long-distance bus and rail systems could also help a great deal, resulting in fewer cars but also encouraging people to use alternatives to their cars more often.

A 50% reduction in fuel use per kilometre for average new LDVs around the world by 2030, from incremental technology improvements and hybridisation, is possible and is likely to be cost effective even at relatively low oil prices. Net negative CO₂ reduction costs are achievable at least for much of this improvement. But it will be important that the efficiency gains are not simply offset by trends toward ever larger, heavier and faster cars. Policies will be needed both to ensure maximum uptake of efficiency technologies and to translate their benefits into fuel economy improvement. Fuel economy standards perhaps complemented by CO₂-based vehicle registration fees can, and already do, play an important role around the OECD. It is important that non-OECD countries also adopt similar policies, and that all countries continue to update these policies in the future, rather than letting policies expire or stagnate. The Global Fuel Economy Initiative, in which the IEA is a partner, is focused on helping to achieve such outcomes.

Advanced technology vehicles will also play a key role, especially after 2020. Initiatives to promote EVs and PHEVs, and the continuing development of FCVs, will be extremely important. For governments, orchestrating the co-development of vehicle and battery production, recharging infrastructure, and providing incentives to ensure sufficient consumer demand to support market growth, will be a significant near-term challenge. Selecting certain regions or metropolitan areas to work with initially, that are keen to be early adopters, may be an effective approach.

Biofuels for LDVs, as well as for other modes, will play a role over time. Fuel compatibility with vehicles is not likely to be a significant problem, needing only minor modifications to new vehicles in the future. But a transition is needed to much more sustainable feedstocks and approaches to biofuels production. As sustainability criteria and rating systems emerge, policies need to shift toward incentivising the most sustainable, low-GHG, and cost-efficient biofuels while minimising impacts from land-use change. A transition to second-generation fuels from non-food feedstocks will play a key role. This is particularly true in OECD countries, as their current biofuels production is dominated by ethanol from grain crops and biodiesel from oil-seed crops. These compete with food/feed supplies and do not perform well in terms of GHG cost-per-tonne or land-use efficiency.

Shifting passenger travel to more efficient modes such as urban rail and advanced bus systems can play an important role in cutting CO₂. But often it provides many other important benefits, such as lower traffic congestion, lower pollutant emissions and more liveable cities. Policies need to focus on better urban design to cut the need for motorised travel, improving mass transit systems to make them much more attractive, and improving infrastructure to make it easier to walk and cycle for short trips. Rapidly growing cities in developing countries have the opportunity to move toward far less car-oriented development than has occurred in many cities in OECD countries. But it will take strong measures and political will, and support for alternative investment paradigms.

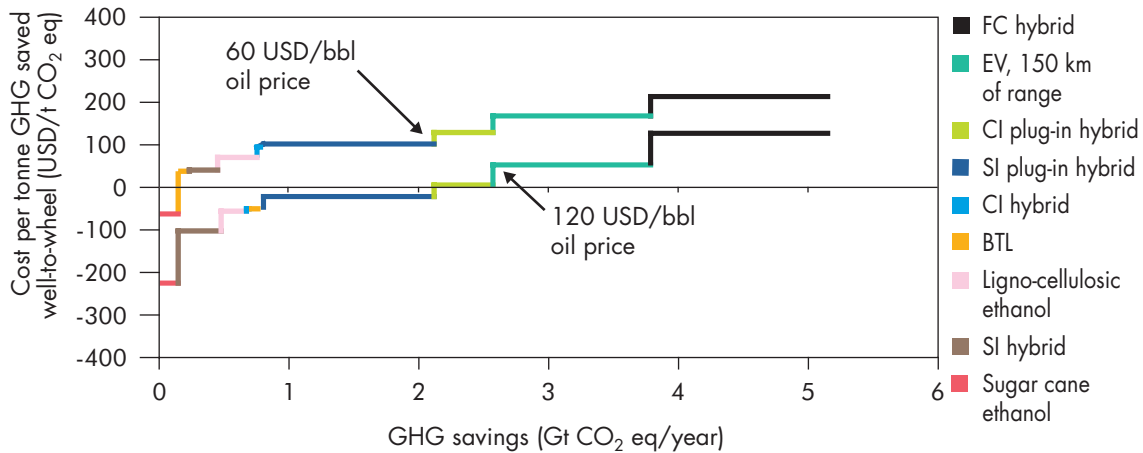
Figure ES-3 shows the role and estimated marginal cost of different technologies and fuels in contributing to CO₂ reductions from LDVs in the BLUE Map scenario in 2050 (modal shifts and non-LDV modes are not included here). These curves are inherently uncertain, and sensitive to small changes in assumptions.³ They show the particular combination of technology and fuels options that are deployed in the BLUE Map scenario, but other combinations could also achieve the same or similar outcomes in terms of CO₂ reductions.

Despite the uncertainties, the results are revealing. By 2050, deep reductions in CO₂ equivalent GHG emissions from LDVs, on the order of 5 Gt, appear possible at a marginal cost of about USD 200/tonne with oil at USD 60/bbl. A second case, assuming a higher oil price of USD 120/bbl, is also shown. At this higher oil price, the emissions reductions are achieved at a marginal cost of about USD 130/tonne. Most of the emissions reduction is achieved at costs far below this. In earlier years, particularly up to 2030, most cost reductions come

3. Costs in 2050 are particularly uncertain as they are partly dependent on earlier deployment, which triggers learning and cost reductions. Given the close position of various options in terms of cost per tonne, the "rank order" of different options could easily change. Further, options were selected on a wider set of criteria than just cost-minimisation, such as the portfolio benefit of deploying multiple low-GHG vehicle and fuel types.

from incremental improvements to internal combustion engine (ICE) vehicles and hybridisation, at very low average cost.

Figure ES-3 ► **GHG reductions in BLUE Map for light-duty vehicles and fuels: contribution and estimated cost per tonne by vehicle and fuel type in 2050**



Note: SI = spark ignition (gasoline) vehicle; CI = compression ignition (diesel) vehicle; ICE = internal combustion engine vehicle; “hybrid” refers to hybrid-electric vehicle; BTL = biomass-to-liquids biodiesel; FC = fuel cell; EV= electric vehicle.

Key point

Substantial low-cost GHG reduction opportunities appear available, especially at higher oil prices.

Trucks and freight movement

Trucking has been one of the fastest-growing modes in most countries over the past ten to 20 years. This growth is likely to continue in the future, although possibly with some decoupling from gross domestic product (GDP) as an increasing share of economic growth comes from information and other non-material sectors. Trucks have also become more efficient over time. But there remain major opportunities to improve efficiency still further, through technical measures, operational measures such as driver training, and logistical systems to improve the efficiency in the handling and routing of goods.

Through better technologies (such as advanced engines, light-weighting, improved aerodynamics, better tyres), new trucks can probably be made 30% to 40% more efficient by 2030. More information is needed on technology costs. But many of the improvements appear likely to be quite cost effective, perhaps reflecting more significant market failures in terms of truck operators adopting cost-effective technologies than is often believed. Logistic systems to ensure better use of trucks, and shifts to larger trucks in some cases, can provide additional efficiency gains system wide, and may also be quite cost effective. But to maximise the gains, governments will need to work with trucking companies, for example through supporting driver training programmes and to create incentives or requirements for

improved efficiency. Japan's Top-Runner Program efficiency requirements for trucks are the first of their kind in the world.

Trucks can use biodiesel fuel very easily, especially the very high quality biodiesel that comes from biomass gasification and liquefaction. Given that for many trucks shifting to electricity or hydrogen will be difficult, for example due to range requirements and energy storage limitations, the development of such second-generation biofuels may be the only way to substantially decarbonise trucking fuel.

Modal shift to rail continues to be an attractive option to save energy and cut CO₂ emissions, given the inherently efficient nature of rail. Many countries currently move only a small share of goods by rail. But to achieve shifts, very large investments in rail and intermodal systems will be necessary in most countries.

Aviation

Air travel is expected to be the fastest-growing transport mode in the future, as it tends to grow even faster than income during normal economic cycles. Air passenger kilometres increase by a factor of four between 2005 and 2050 in the Baseline scenario, and by a factor of five in the High Baseline scenario. Aviation benefits from steady efficiency improvements in each generation of aircraft, and this is likely to continue. But given the expected very high rate of activity growth, aviation energy use and CO₂ emissions are expected to triple in the Baseline scenario and quadruple in the High Baseline scenario.

An increase in the rate of efficiency improvements beyond Baseline rates may be possible, by encouraging aircraft manufacturers to make bigger gains with each generation of aircraft and by improving air traffic control. A wide range of fuel efficiency technologies for aircraft remain unexploited, including aerodynamic improvements, weight reduction and engine efficiency, with an estimated overall potential to make average aircraft nearly twice as efficient in 2050 as they are today. Improved air traffic control can also improve the overall fuel efficiency of aviation. Savings are in the order of 5% to 10%. More work is needed better to understand the cost-effectiveness of various options, although a few available estimates suggest that some may be quite cost-effective. One significant factor in assessing technology cost-benefit for aircraft is that aircraft burn large quantities of fuel over their lifetimes; up to 1 billion litres of jet fuel for a very large aircraft. Thus, cutting fuel use can provide enormous fuel cost savings. This suggests that even major investments to improve aircraft efficiency may be cost-effective, at least using a long-term, societal cost perspective.

Measures to encourage faster introduction of new technologies on successive generations of aircraft, reflecting very high societal benefits, can help. This can also be promoted by international agreements that price or limit aviation GHG emissions. However, GHG reduction is complicated by the fact that CO₂ is just one of several aircraft emissions that have radiative forcing (i.e. climate warming) effects. Others include nitrogen oxides, methane, water vapour and cloud formation. Much more work is needed to better understand the net effects and optimal strategies for reducing overall aviation GHG emissions.

Even more than trucks, aircraft are restricted in the types of fuels they can use. The energy density of liquid fuels is critical for providing adequate aircraft flying range, so shifting to gaseous fuels or electricity appears impractical (liquid hydrogen may be a viable option, but requires major compromises in other airplane design features). Thus, high quality, high energy-density aviation biofuels are of great interest to airlines and aircraft manufacturers, as these may hold the best hope of providing low-GHG fuels in the future. But the concerns expressed above regarding biofuels sustainability and feedstock supply apply to aircraft as they do for other modes. In the BLUE Map scenario, 30% of aircraft fuel is second-generation biofuel, such as biomass-to-liquid (BTL) fuel, by 2050.

Modal shift and a general reduction in aviation travel growth can help. In the BLUE Shifts scenario, air travel growth is cut by 25%, resulting in a tripling by 2050 rather than quadrupling. This will, to some extent, occur naturally if alternatives such as high-speed rail systems are provided, but it must also be encouraged by policies that, for example, help ensure the availability and cost-competitiveness of rail travel. Substituting telematics (such as teleconferencing) for some long-distance trips could also play an important role, and could also be encouraged by governments as well as by businesses.

Shipping

International water-borne shipping has grown very rapidly in recent years, in particular as a function of the growth in Asian manufacturing and exports to other countries. It now represents about 90% of all shipping energy use, the remainder being used in-country by river and coastal shipping. Container shipping fuel use has risen the fastest, and may rise much more in the future; projections of up to an 8-fold increase for container shipping to 2050 have been made. The average size of ships is also rising, such that shipping is becoming steadily more efficient per tonne-kilometre moved, although practical limits to ship size may be at hand.

Apart from size increases, ship efficiency has not clearly been improving significantly in recent years. The structure of the shipping industry – with fragmented and very different systems of ownership, operation and registration often all happening in different countries for a given ship – may serve to limit the market incentives to optimise ship efficiency.

Many potential efficiency improvement measures have been identified. About 50 are outlined in the shipping chapter of this publication. If most of these options were adopted, it is estimated that a 50% or greater reduction in energy use per tonne-kilometre could be achieved, even taking into account various interactions between options. More research on cost is needed, but recent research suggests that many options for retrofitting existing ships could achieve substantial energy and CO₂ savings at very low or net negative cost.

As for aircraft, biofuels hold important potential for decarbonisation of shipping fuel. Ship engines are capable of using a wide range of fuels, and may be able to use relatively low quality, low-cost biofuels. In the BLUE Map scenario, 30% of ship fuel by 2050 is low GHG biofuel.

Policies to promote improved international shipping efficiency and CO₂ reduction may have to come from international agreements. Shipping could be included in a CO₂ cap-and-trade system. Another proposal has been to develop a ship efficiency index, and to score all new and existing ships using the index. This could be coupled with international incentives or regulations on new ship efficiency and used to encourage modifications to existing ships, given that many efficiency retrofit opportunities are available. But more work is needed to develop such an index, in particular to estimate the efficiency benefits and costs for various types of improvements. The UN International Maritime Organisation (IMO) has a lead role in such efforts, although separate efforts are also needed to provide multiple viewpoints and sources of information.

The role of international co-operation

A significant reduction in CO₂ emissions in transport will only be possible if all world regions contribute. Although transport CO₂ per capita is far higher today in OECD than in non-OECD countries, nearly 90% of all the future CO₂ growth is expected to come from non-OECD countries. In the IEA BLUE scenarios, all regions cut transport CO₂ dramatically compared to the Baseline in 2050. Vehicles can be made much more efficient in all parts of the world, generating large fuel savings. Changes in travel can also occur, although in many countries the main priority needs to be to preserve current low-energy travel modes. Alternative fuels, if their costs can eventually approach those for oil-based fuels, will also be welcomed world wide.

Governments will need to work together – and with key stakeholders – to ensure that markets around the world send similar signals to consumers and manufacturers, in part to maximise efficiency and limit the cost of future changes. Common medium- and long-term targets in terms of fuel economy, alternative fuels use, and even modal shares would send clear signals to key players and help them begin to plan. For those producing efficient products, knowing that a wide range of markets will be eager for those products will help plan production and, through market size, cut costs. The Global Fuel Economy Initiative represents an important example of moving toward greater international co-operation in developing targets and standards.

In addition to setting and reaching efficiency targets, national governments need to work together and with key stakeholders to develop and deploy new types of very low-GHG vehicles and fuels. Technologies such as electric and fuel cell vehicles can only be introduced into markets in which there is adequate refuelling infrastructure, and consumers are willing and ready to purchase both the vehicles and the fuels. Markets alone will have difficulty achieving such outcomes. Governments must lead in orchestrating such transitions, and to help overcome the risks involved.

Most new technologies need government support while in the RD&D phase, before they become commercially viable. There is an urgent need for major acceleration in co-ordinated RD&D in breakthrough technologies. This needs to be coupled with the introduction of a range of policy measures that will create clear international targets and predictable, long-term economic incentives for new low-GHG technologies.

Roadmaps can help show what is needed to take technologies from their current status through to full commercialisation, and to outline the role of industries, governments and other stakeholders in achieving various outcomes. The IEA is developing energy technology roadmaps with broad international participation and in consultation with industry. These roadmaps will enable governments, industry and financial partners to identify the steps needed and co-operate to implement measures that will accelerate technology development and uptake. The IEA is currently completing a roadmap for electric and plug-in hybrid vehicles, and will launch other roadmaps in areas such as biofuels, advanced ICEs and fuel-cell vehicles in the near future.

Conclusion

This report shows that transport can achieve deep reductions in energy use and GHG emissions by 2050 through a combination of approaches, and with a mix of incremental and advanced technologies. In the long term, costs are expected to come down such that by 2050, the goals may be reached at a marginal cost of about USD 200 per tonne. But the transition to 2050 will include deploying some relatively high-cost options, and cost reductions are not assured. Strong RD&D programmes are needed to speed cost reductions and the market introduction of advanced technologies. These include electric and fuel cell vehicles, but also advanced designs for trucks, ships and aircraft; advanced, sustainable biofuels; and telematic and ITS systems to improve the efficiency of transport systems.

2050 is only 40 years away. To put transport on a sustainable pathway within that timeframe, current trends must be changed substantially within the next five to ten years. Strong policies are needed very soon to begin to shift long-term trajectories and to meet interim targets. While key long-term technologies such as advanced biofuels, electric and fuel cell vehicles are being developed and deployed, governments need to push hard for the efficiency of today's vehicles to be improved, and for the deployment of transition technologies such as plug-in hybrid vehicles. Strong measures are also needed in terms of investments in infrastructure and incentives that can influence how people choose to travel and enable much greater use of efficient modes. Many measures are already in place in different parts of the world. But stronger measures will be needed, and must be pursued with renewed vigour. Greater international co-operation can play a key role in sharing experience and overcoming obstacles to reaching sustainability.

Chapter 1 TRANSPORT TRENDS AND FUTURE SCENARIOS

Key findings

- ▶ Driven by increases in all modes of travel, but especially in passenger light-duty vehicles (LDVs) and aviation, the Baseline projection of energy use in transport increases by nearly 50% by 2030 and 80% by 2050. In a new High Baseline scenario, it increases by 130%. Carbon dioxide (CO₂) emissions increase at even faster rates, due to increased use of high CO₂ fuels such as coal-to-liquids after 2030. Transport CO₂ emissions nearly double from about 7.5 Gt in 2006 to about 14 Gt in 2050 in the Baseline scenario and 18 Gt in the High Baseline scenario¹.
- ▶ The analysis presented throughout this publication includes BLUE Map and BLUE EV Success scenarios similar to those in Energy Technology Perspectives 2008, ETP 2008 (IEA, 2008a). It also includes a new BLUE Shifts scenario, which is focused on changes in the shares of passenger travel and freight transport by mode, with reductions in the growth of LDV, truck and air travel, and higher growth for buses and rail travel. In the BLUE Shifts scenario, over 2 Gt of CO₂ are saved world wide in 2050 compared to the Baseline scenario.
- ▶ In the BLUE Map scenario, a saving of over 9 Gt of CO₂ by 2050 results in total emissions of 4.5 Gt compared to 14 Gt in the Baseline scenario. Very strong efficiency improvements in all modes, especially in LDVs, but also in trucks, buses, ships, rail and aircraft, account for about half of this reduction. The other half is provided by a reduction of petroleum fuels share to 50% of all fuels, displaced over time by low CO₂ biofuels, electricity and hydrogen.
- ▶ When the BLUE Map scenario is combined with the BLUE Shifts scenario (BLUE Map/Shifts), CO₂ emissions in 2050 are 10 Gt lower than in the Baseline scenario. Although interactions between measures mean that the contribution of each of modal shifts, efficiency and alternative fuels is less than when the scenarios are run separately, each still provides an important contribution. As shown in subsequent chapters, each of these appears likely to be able to provide a substantial contribution at relatively low cost per tonne of CO₂ saved, though some alternative fuels options may be costly in the near term.
- ▶ In total, the BLUE Map/Shifts combined scenario cuts transport-related CO₂ to 4 Gt in 2050. This represents a reduction of more than 70% compared to the Baseline scenario and nearly 80% compared to the High Baseline scenario in 2050, and a 40% reduction compared to 2006 levels.

1. This is actually CO₂-equivalent (CO₂-eq) GHG, including CO₂, N₂O and CH₄, emitted during fuel production. However, it does not include non-CO₂ GHG emissions from vehicles, which can be significant for some types, such as aircraft. This convention is used throughout this report. In many places, CO₂-eq is shortened to CO₂ for simplicity.

- ▶ *The reductions in energy use and CO₂ emissions in 2050 in the BLUE Map/Shifts scenario occur world wide, reflecting more sustainable and efficient travel in all regions. Virtually all countries' and regions' emissions from transport are at least 50% lower than in the Baseline scenario in 2050. But not all regions reach outright reductions compared to their 2006 levels. The biggest reductions occur in the OECD regions, albeit from a much higher per capita starting point than in other regions. CO₂ emissions in OECD countries in 2050 drop by 60% to 70% below 2006 levels. India and China's emissions still grow but far less than in the Baseline. The rest of the world's emissions drop by an average of around 30% below 2006 levels.*

Introduction

As shown in *ETP 2008*, the global energy economy is on a path to roughly double its energy use and CO₂ emissions by 2050. Transport accounted for about 23% of energy-related CO₂ emissions in 2005 and is likely to have a higher share in the future unless strong action is taken.

Reducing fossil energy use in transport worldwide will be extremely challenging. But *ETP 2008* showed that, if a halving of 2005 energy-related CO₂ emissions is to be achieved by 2050, transport must make a significant contribution. In the analysis, transport CO₂ emissions in 2050 are reduced to about 20% below their 2005 levels.

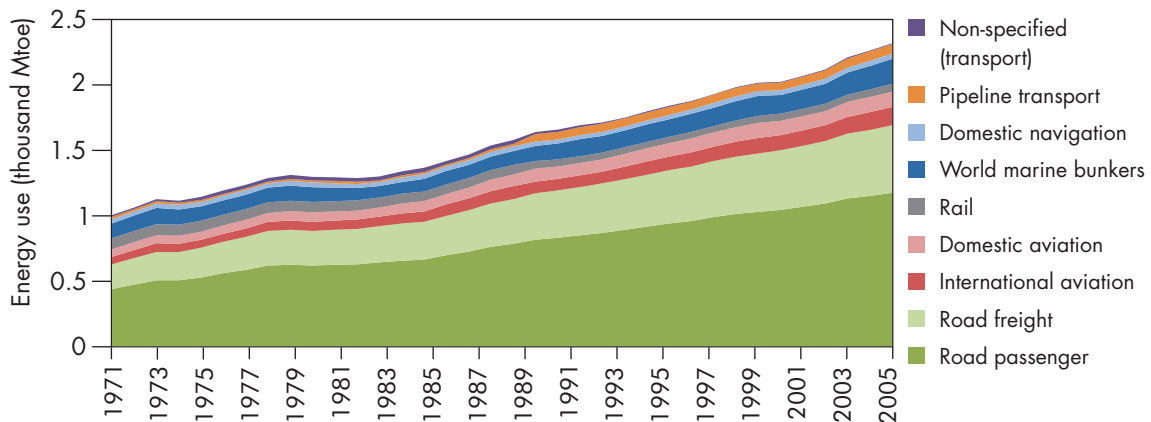
The aim of *Transport, Energy and CO₂: Moving towards Sustainability* is to help policy makers and stakeholders explore different possible transportation energy futures and identify transport technologies and policies that will move the world economy onto a sustainable, lower CO₂ track. The analysis starts from the transport chapter of *ETP 2008* and extends that analysis in a number of respects, including the development of new future scenarios. As in *ETP 2008*, the focus here is on the movement of people and goods, and the associated energy use and GHG emissions.

Worldwide, transport sector energy and CO₂ trends are strongly linked to rising population and incomes. Transport continues to rely primarily on oil. Given these strong connections, decoupling transport growth from income growth and shifting away from oil will be a slow and difficult process. In projecting trends, this inertia must be taken into account. Large reductions in GHG emissions by 2050 can only be achieved if some of the elements contributing to the inertia of transport-related energy demand growth are overcome, so that change can happen much more quickly in the future than it has in the past. For example, improvements in vehicle and system efficiencies of 3% to 4% per year will need to replace past improvement rates of 0.5% to 1%. New technologies and fuels will need to be adopted at unprecedented rates.

Worldwide mobility and energy use trends

From 1971 to 2006, global transport energy use rose steadily at between 2% and 2.5% per year, closely paralleling growth in economic activity around the world (Figure 1.1). The road transport sector (including both LDV and trucks) used the most energy and grew most in absolute terms. Aviation was the second-largest user of energy and grew the most in relative terms.

Figure 1.1 ▶ World transport energy use by mode, 1971-2006



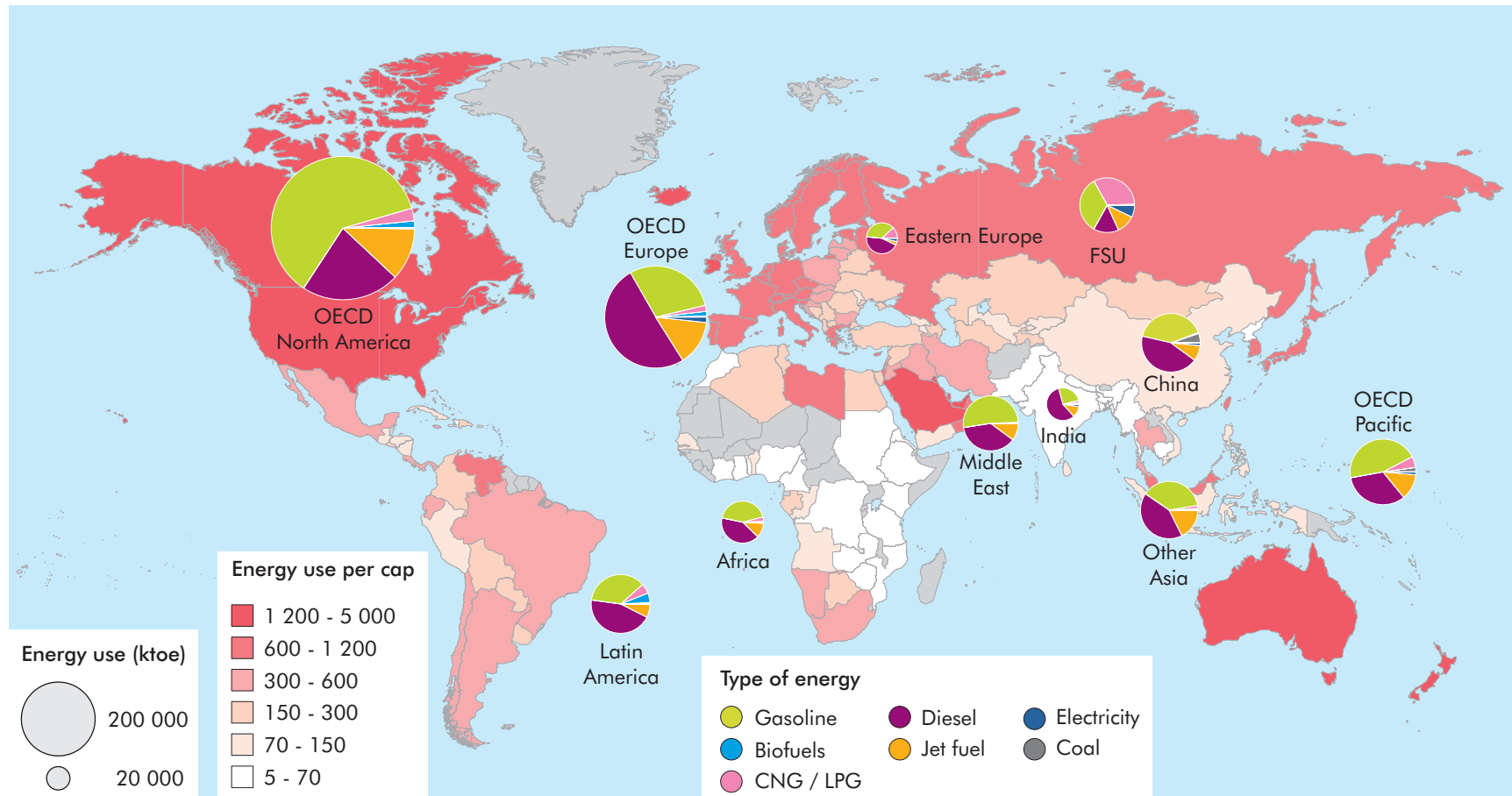
Key point

Transport energy use has more than doubled since 1971, and has been dominated by road transport.

In recent years, particularly since 2000, the picture has changed in important ways. As shown in Table 1.1, transport energy use in OECD countries grew by an average of just over 1% per year between 2000 and 2005, rather than the more than 2% per year shown in the previous decade. Aviation, which had previously had the highest growth rate of all modes within OECD countries, fell to amongst the lowest following the events of 11 September 2001, before recovering to its previous growth levels after 2005 at least until 2008. Growth in transport energy use in non-OECD countries accelerated continuously from 2000, such that its overall growth rate since 1990 was higher than that for OECD countries. If incomes continue to rise rapidly in non-OECD countries, rapid transport growth can be expected to continue. Population will also grow much more rapidly in non-OECD countries than in OECD countries. In contrast, in OECD countries, there are signs of saturation of some types of travel. For example, the growth in passenger LDV ownership appears likely to slow significantly in the future, irrespective of the effects of economic cycles.

Various regions and countries show very different patterns in terms of both energy use per capita and the types of fuel used (Figure 1.2). Some regions, such as North America (except Mexico) averaged over 1200 ktoe per person in 2006, while some, such as parts of Africa, averaged less than 100 ktoe per person. These data reveal differences both in the amount of travel undertaken and in the fuels used for that travel. The relative efficiency of vehicles is a much smaller factor in overall energy use.

Figure 1.2 ▶ Transport sector energy use per capita, 2006



The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Note: Does not include international shipping.

Source: IEA statistics.

Key point

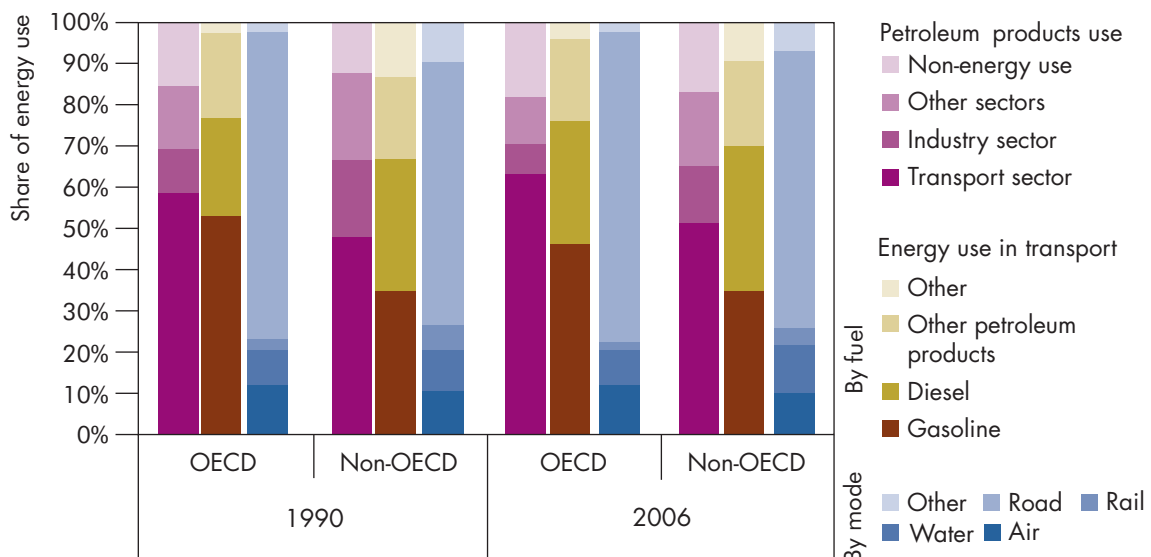
Different countries have very different patterns of energy use per capita and by types of energy used.

Table 1.1 ► Growth rates of transport energy use, 1990-2006

	Year Period	OECD				Non-OECD			
		90-95	95-00	00-06	90-06	90-95	95-00	00-06	90-06
Type of Transport	International aviation	4.4%	5.0%	1.2%	3.4%	-0.6%	1.7%	4.7%	2.1%
	Domestic aviation	-0.2%	2.5%	-0.3%	0.6%	-0.5%	4.9%	3.0%	2.5%
	Road	2.3%	2.1%	1.4%	1.9%	2.5%	2.9%	4.2%	3.3%
	Rail	-0.1%	-0.3%	2.3%	0.7%	-4.4%	2.9%	2.3%	0.3%
	International marine bunkers	1.1%	2.3%	2.5%	2.0%	4.6%	3.9%	5.4%	4.7%
	Domestic navigation	0.8%	0.5%	-1.0%	0.0%	-2.6%	6.5%	4.0%	2.6%
Transport sector		2.1%	2.1%	1.2%	1.8%	1.1%	2.6%	4.3%	2.8%

Source: IEA statistics.

Transport depends very heavily on oil and oil products. Most of the oil consumed worldwide is used in transport. In particular, nearly all the recent growth in oil use comes from growth in transport. As shown in Figure 1.3, more than 60% of the petroleum products used in OECD countries and about half of those used in non-OECD countries were used as transportation fuels, a higher proportion in both regions than in 1990. Energy diversification within the transport sector has been a high priority for many oil-importing countries in the last few decades. But very few

Figure 1.3 ► Cross dependencies of transport on oil, and of oil on transport

Source: IEA statistics.

Key point

Oil use and transportation are very interrelated. The dependency has increased between 1990 and 2006.

countries, other than Brazil, have made much progress on this aim. Transport relies on oil for more than 95% of its needs worldwide.

There are a number of reasons for this dependence. Oil and oil products such as gasoline and diesel fuel have proven to be extremely effective transport fuels, with high energy density and relatively easy handling/transportation characteristics. Oil prices have been low on average compared to available alternatives over the past 20 years. In addition, most alternative fuels require new types of vehicles and extensive investments in new infrastructure and fuel delivery systems that make it difficult for them to compete, given the extensive oil-based vehicle stock and infrastructure already in place.

Within the transport sector, LDV and trucks account for around 75% of the travel-related energy used in OECD countries and two-thirds of the travel-related energy used in non-OECD countries. Aircraft and water-borne transport account for most of the remainder. These relative shares of energy use have remained fairly stable over the past 15 years as underlying growth in activity, such as the rapid growth in air transport, has been offset by increases in efficiency.

Box 1.1 ► **IEA Mobility Model (MoMo)**

Following work started with the World Business Council on Sustainable Development in 2003, the IEA has continued to develop a global transport spreadsheet model that supports projections and policy analysis. This is now called the Mobility Model (MoMo). MoMo contains historical data and projections to 2050, and includes all transport modes and most vehicle types, including two- and three-wheelers, passenger cars, light trucks, medium and heavy freight trucks, buses and non-road modes (rail, air and shipping). The model development has been supported by BP, Honda, Nissan, Shell, StatoilHydro, Toyota and Volkswagen.

MoMo now covers 22 countries and regions. It contains a good deal of technology-oriented detail, including underlying IEA analyses on fuel economy potentials, alternative fuels, and cost estimates for most major vehicle and fuel technologies, with cost tracking and aggregation capabilities. It therefore allows fairly detailed bottom-up “what-if” modelling, especially for passenger LDVs. Energy use is estimated using an adapted version of the ASIF methodology, which helps to ensure consistency between activity (passenger and freight distances travelled), structure (load factors per vehicle), energy intensity (fuel economies of different vehicles) and fuel factors (IEA, 2000). This is fully applied for passenger LDVs and, as of 2009, for light, medium and heavy trucks. For other modes, a simplified version of the ASIF methodology is applied.

This approach is based on:

- *Stock (total stock of vehicles by type and region).*
- *Travel (average travel per vehicle by type and region).*
- *Fuel consumption (average fuel use per kilometre by vehicle type and region).*
- *Energy use (derived as the product of the first three).*

The results are then checked against IEA energy use statistics to ensure that the identity is solved correctly for each region. For non-passenger LDV and truck modes, a simpler approach is necessary until sufficient travel activity data is developed to undertake a full ASIF approach. The methodology adopted for each mode and transport sector has been influenced by the data availability for each region of the world.

MoMo produces projections of vehicle sales, stocks (via a scrappage function) and travel; it also tracks energy use, GHG emissions (on a vehicle and well-to-wheel basis) and pollutant emissions for all modes. It provides estimates of the demand for materials needed for the production of LDVs. All main transport fuels, including biofuels, hydrogen, electricity and synthetic fuels, are considered. Projections of safety (fatalities and injuries) are also incorporated, though these have not been updated since 2004.

More information on MoMo and this methodology is provided in Appendix A.

Transport activity

In the absence of reliable statistics on such variables as vehicle sales, stocks and travel amounts, collected and reported systematically around the world, data must be collected on an *ad hoc* basis. For its transport modelling work, the IEA has developed a mobility database in conjunction with MoMo (see Box 1.1). This is improved progressively in order to try to better understand the trends in and influences on transport energy use. The IEA is also working with the United Nations Environment Program (UNEP) to gather fuel economy information through a global fuels and vehicles database project for developing and transitional countries.

Several countries publish figures on vehicle sales and vehicle stocks, and independent sources for data exist for most countries. But reliable data on average travel and average intensity is more difficult to obtain. The MoMo methodology enables the reliability of existing data to be established, by ensuring consistency.

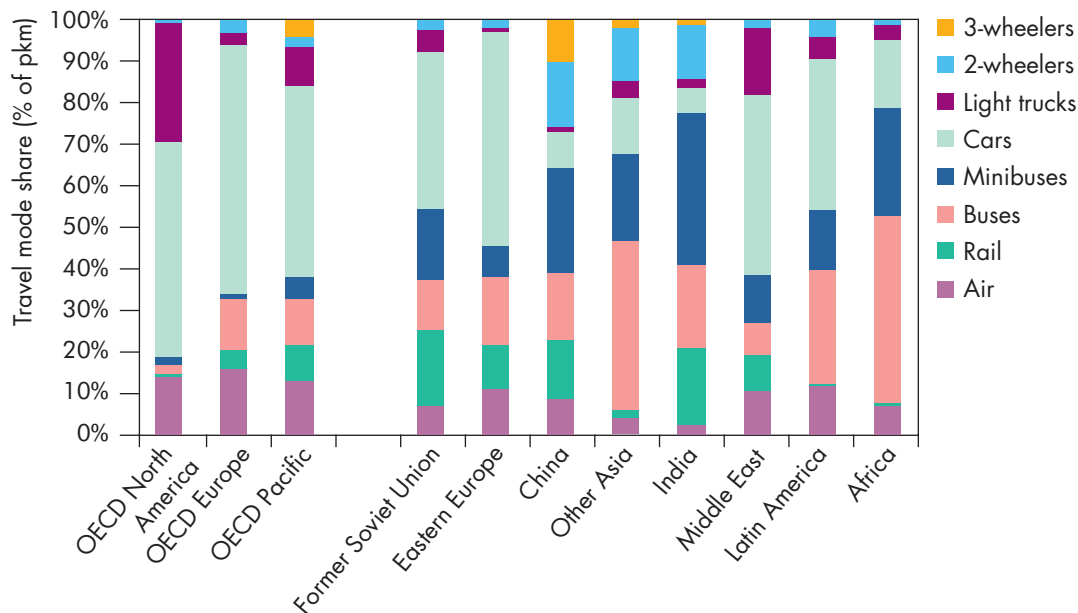
An understanding of trends in passenger behaviour (e.g. distances travelled, modal choice) is needed fully to appreciate the significance of the data that are available. Unfortunately, although passenger travel data is often available at an urban level, it is difficult to obtain data on a national or regional level. Even among most OECD countries, there is no systematic or regular approach to conducting mobility surveys. But, by applying available data on load factors (*i.e.* the average numbers of passengers per vehicle) it is possible from the MoMo data to estimate passenger travel by mode. The IEA has attempted to derive passenger travel by mode and region on this basis. This can serve as a first approximation until better direct data on passenger travel become available. There remains a need for mobility surveys, using a consistent methodology, to be undertaken at the country level.

Freight transport data do not suffer from this issue to the same extent. Fairly robust data on the volumes of freight movement (in tonne-kilometres – tkm) exist for many countries. In the MoMo, the number of vehicles that will be needed to move projected volumes of freight is determined by dividing volumes by the relevant load factors for different modes.

Recent trends in passenger travel

Using the MoMo data as described in the previous section, regional averages for the shares of travel undertaken by different motorised modes in 2005 are shown in Figure 1.4. This excludes non-motorised modes of travel (such as walking and bicycling) because there is little data on these modes and they do not use fuel. OECD countries rely on four-wheel LDVs far more than non-OECD countries. People in OECD countries also undertake far more air travel per person. Developing countries show far higher modal shares for buses and, in some regions, motorised two-wheelers, i.e. scooters and motorcycles. Chapter 3 explores issues related to data and policy in respect to passenger travel.

Figure 1.4 ▶ Motorised passenger travel split by mode, 2005



Source: IEA Mobility Model database estimates.

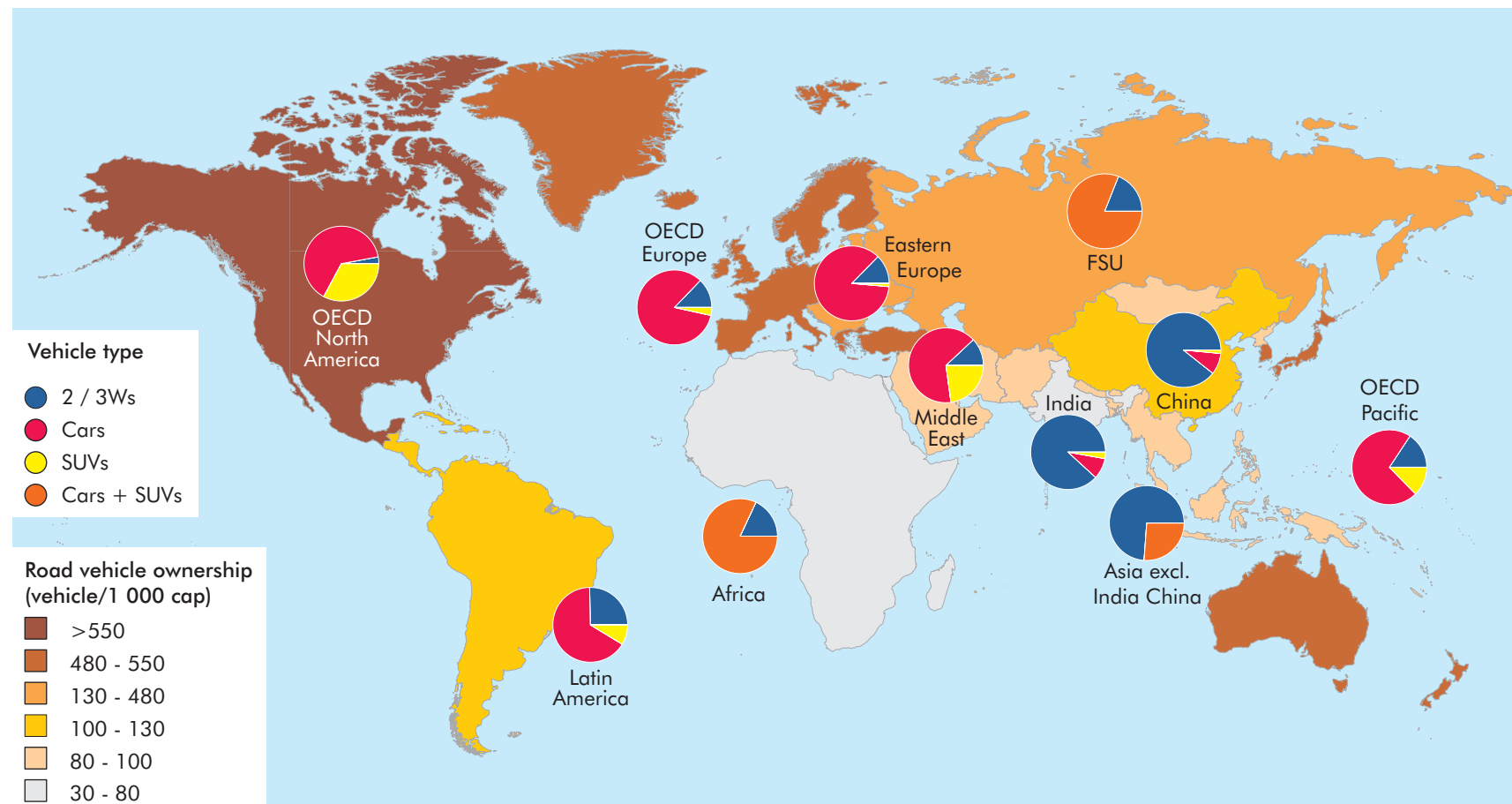
Key point

Passenger travel shares on a passenger-kilometre basis in OECD regions are primarily met by passenger LDVs, while in non-OECD regions buses provide a majority of passenger travel.

The total worldwide stock of passenger LDVs has grown steadily, reaching about 800 million worldwide in 2005. From 1990 to 2005, the stock of LDVs grew by about 60%, or about 3% per year, dominated by gasoline vehicles in most countries. In the same period, world population grew by 25%, from 5.2 billion to 6.5 billion. LDV trends are analysed in more detail in Chapter 3.

In wealthy countries, the rate of growth in passenger LDV ownership has declined in recent years. This may reflect a slowing down in population growth. But it is also possible that more people may be choosing not to own an automobile or as a family choosing to own only one LDV instead of two or more, when there is increased access to mass transit options. Recent surveys in Japan show that the

Figure 1.5 ▶ Passenger LDV stock, by type and region, 2005



The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source: IEA Mobility Model database.

Key point

Two- and three-wheelers greatly outnumber passenger LDVs in Asia.

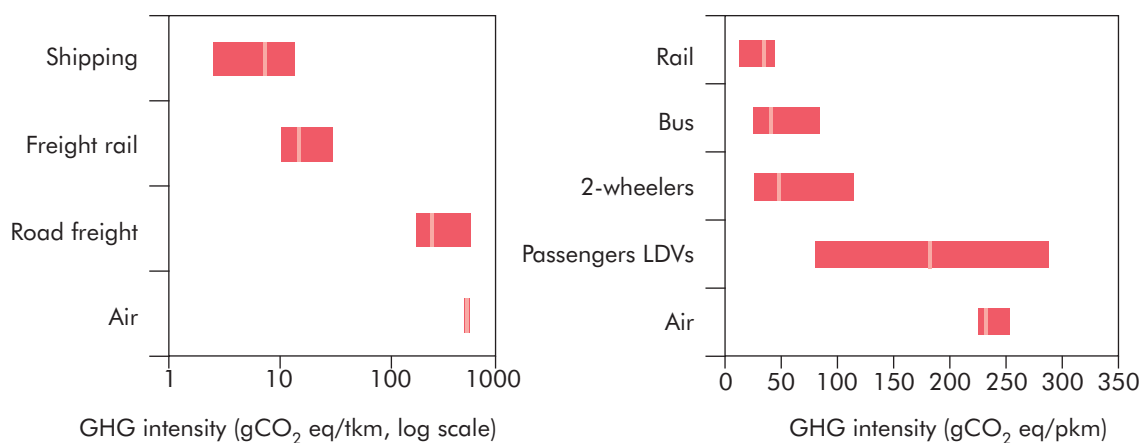
younger generation has to some degree lost interest in LDVs, and focuses more on new communication devices such as mobile phones or laptop computers. But in developing countries, rates of car ownership are growing rapidly, suggesting that mass transit options are insufficient. Many families purchase LDVs as soon as they can afford them. The emergence of low-cost cars, such as the Tata Nano in India, will probably further accelerate LDV ownership rates. The number of motorised two-wheelers also continues to grow rapidly.

Figure 1.5 shows the worldwide rates of passenger LDV and two- and three-wheeler ownership in 2005, and the share of each type. Although two- and three-wheel vehicles represent more than half of the vehicles in Asia, they only account for a small proportion of the total travel as two-wheelers are usually driven shorter distances, and much of the time carry fewer people than LDVs. There is a wide range of two-wheeler ownership, with the highest concentrations in Asia and very low levels in North America. It is not clear whether, as passenger LDV ownership rises in Asia, the ownership and use of two-wheelers will begin to decline. However, if congestion is acute, two-wheelers may still be the easiest way to get around.

Energy efficiency by mode

Estimates of recent average vehicle efficiencies by mode are shown in Figure 1.6, in grams of CO₂ eq per tonne-km for freight modes and in GHG per passenger-km for passenger modes. The same pattern would emerge if the x-axis was in energy units rather than grams of CO₂. The figures reveal a wide range of values for each mode of transport, the range corresponding to the lower and higher boundary of the geographical zones considered in MoMo and the average value being shown as a vertical line. Some modes are generally more efficient than other modes: for

Figure 1.6 ► GHG efficiency of different modes, freight and passenger, 2005



Note: The clear line indicates world average, the bar representing MoMo regions' discrepancy.

Sources: IEA Mobility Model database; Buhaug (2008).

Key point

The energy efficiency and CO₂ emissions of different passenger and freight modes vary widely; shipping is most efficient, air is usually the least efficient.

example, rail is more efficient than air in both freight and passenger movement. But the most efficient mode can depend on the range of travel: for example, passenger air travel is generally less efficient than passenger LDV travel, except for over very long distances. These efficiency values can be heavily influenced by average loads or ridership. For example, buses in the United States have significantly higher CO₂ emissions per passenger-km than those in most other parts of the world, where buses tend to be fuller.

It is clear from this analysis that shipping is generally the most efficient way to move freight. Rail is the next most efficient mode. Road and air freight movements tend to be much more energy intensive. For passenger transport, rail, buses and two-wheelers show similar levels of average efficiency, but efficiency levels range much more widely for buses and two-wheelers than for rail. Passenger LDV efficiencies range even more widely, reflecting the fact that different regions have very different vehicle types as well as significant differences in average load factors. Air travel shows a narrower range but on average emits more CO₂ than any other mode.

Projections and scenarios

The analysis presented in *ETP 2008* has been updated and is presented here in more detail. A few new features have been added. Changes from the transport analysis in *ETP 2008* include:

- The Baseline scenario projection has been updated to reflect the more recent World Energy Outlook 2008, *WEO 2008* (IEA, 2008b). This results in a slight lowering of most transport activity and fuel use projections due to lower GDP growth and higher oil prices than projected in the previous *WEO 2007*. A new scenario, High Baseline, has also been developed to explore the potential energy and CO₂ impacts of even higher growth than in the Baseline scenario.
- Additional analysis is presented in the BLUE Shifts scenario on the potential impacts of passenger and freight modal shifts. These shifts enable larger reductions in overall energy use and CO₂ emissions than those achieved in the BLUE Map scenario.
- Technology potentials and costs, in particular for LDVs and a range of fuels, have been updated and are presented in more detail than in *ETP 2008*.
- Additional analyses for surface freight transport, shipping and air travel have been undertaken, though cost estimates for technologies and measures in those sectors remain uncertain and need additional development.

The Baseline scenario represents a projection reflecting the absence of new policies to change expected future trends. Using the IEA MoMo, a number of additional scenarios have been developed to show how the transport sector might look in 2050. These scenarios represent just a few of very many other possible futures, selected to illustrate the impacts of specific policy and technology developments. They are not predictions.

Scenarios covered in this publication

Five main scenarios are covered in this publication. Two represent futures with different growth assumptions, both without any strong policy intervention to change how trends may develop. Three are policy-driven scenarios that highlight different interventions designed to cut energy use and GHG emissions from the transport sector. The scenarios are outlined below. The key assumptions for each of these scenarios are summarised in Table 1.2.

- **Baseline** – vehicle ownership and travel per vehicle for LDVs, trucks and other modes are consistent with *WEO 2008* and a world oil price of USD 100/bbl rising to USD 120/bbl by 2030. This scenario implies somewhat lower passenger LDV ownership in the developing world, at a given level of income, than has occurred historically in many OECD countries. This could be caused by a number of factors including greater urbanisation in developing countries and lower suburbanisation than in OECD countries, greater income disparities between the wealthy and the poor in non-OECD countries, and limits on the infrastructure needed to support large numbers of vehicles. This scenario also assumes a continuation of the decoupling of freight travel growth from GDP growth around the world, which has clearly begun in OECD countries.
- **High Baseline** – this scenario assumes higher growth in passenger LDV ownership in the developing world to levels more consistent with historical trends in OECD countries, and faster growth in vehicle travel and freight transport, especially trucking. This scenario results in about 20% higher fuel demand by 2050 and would probably require much greater use of more expensive fossil fuels, such as unconventional oil, coal- and gas-to-liquid synthetic fuels.
- **BLUE Map** – this scenario broadly reflects the BLUE Map presentation in *ETP 2008*. It reflects the uptake of technologies and alternative fuels across transport modes that can help to cut CO₂ emissions at up to USD 200 per tonne of CO₂ saved by 2050. New powertrain technologies such as hybrids, plug-in hybrids vehicles (PHEVs), electric vehicles (EVs) and fuel cell vehicles (FCVs) start to penetrate the LDV and truck markets. Strong energy efficiency gains occur for all modes. Very low GHG alternative fuels such as hydrogen, electricity and advanced biofuels achieve large market shares.
- **BLUE Shifts** – this scenario envisages that travel is shifted towards more efficient modes and a modest reduction in total travel growth as a result of better land use, greater use of non-motorised modes and substitution by telecommunications technologies. Chapter 5 details the assumptions and impacts associated with this scenario for passenger travel, primarily focused on shifting from passenger LDVs and air travel to rail, bus and non-motorised modes. Chapter 6 looks at a range of policies that could be adopted in order to shift passenger travel to other more sustainable modes. Most of these policies will need time to be implemented and to have a wide impact. The scenario envisages that this has happened by 2050, with passenger travel in LDVs and aircraft approximately 25% below Baseline scenario 2050 levels as a result.
- **BLUE EV Success** – this scenario assumes that EVs almost completely displace ICE LDVs by 2050 and that FCVs do not achieve significant market shares. This

Table 1.2 ▶ Scenario descriptions and main assumptions

	Baseline	High Baseline	BLUE Map	BLUE Shifts	BLUE EV Success	BLUE Map/Shifts
Scenario definition	Baseline projection	Non-OECD countries follow more closely OECD passenger LDV ownership trends	Greater use of biofuels, deployment of EVs, FCVs	No advanced technology deployment, gain through modal shifting only	Dominant EVs for LDVs and trucks	BLUE Map+ BLUE Shifts
Passenger light-duty vehicles	Total vehicle travel more than doubles by 2050; fuel economy of new vehicles 30% better than 2005	Total vehicle travel triples by 2050; fuel economy of new vehicles 30% better than 2005	FCVs reach 40% of market share in 2050, so do EVs/PHEVs	Passenger travel in LDVs 25% lower than Baseline in 2050. Ownership and travel per vehicle reduced	EVs reach 90% market share in 2050	BLUE Map+ BLUE Shifts
Trucks	Strong growth through 2050; 25% on-road efficiency improvement	Strong growth through 2050; 25% on-road efficiency improvement	FCVs and EVs each reach up to 25% of stock by 2050	Baseline tkm growth between 2005 and 2050 cut by 50%, shifted to rail	EVs reach 50% of medium truck stock by 2050, 25% of heavy	BLUE Map+ BLUE Shifts
Other modes	Aircraft 30% more efficient in 2050; other modes 5% to 10% more efficient; strong growth in air, shipping	Aircraft 30% more efficient in 2050; other modes 5% to 10% more efficient; strong growth in air, shipping	Aircrafts 40% more efficient per pkm by 2050 from 2005; improved efficiencies for other modes	Baseline air travel growth cut by 25% (from a quadrupling to a tripling compared to 2005) Many short-distance flights replaced by high-speed rail	Similar to BLUE Map	BLUE Map+ BLUE Shifts
Biofuels	Reaches 260 Mtoe in 2050 (6% of transport fuel) mostly 1st-generation	Reaches 340 Mtoe in 2050 (6%), mostly 1st-generation	Reaches 850 Mtoe in 2050 (33%), mostly 2nd-generation biofuels growth after 2020	Reaches 200 Mtoe in 2050 (6%), mostly 1st-generation	Similar to BLUE Map	Reaches 670 Mtoe in 2050 (32%) mostly 2nd-generation biofuels growth after 2020
Low GHG hydrogen	No H ₂	No H ₂	220 Mtoe in 2050	No H ₂	No H ₂	170 Mtoe in 2050
Electricity demand for transport	25 Mtoe (mainly for rail)	30 Mtoe (mainly for rail)	390 Mtoe in 2050 primarily for EVs and PHEVs	40 Mtoe (mainly for rail)	580 Mtoe in 2050 primarily for EVs and PHEVs	330 Mtoe in 2050 primarily for EVs and PHEVs

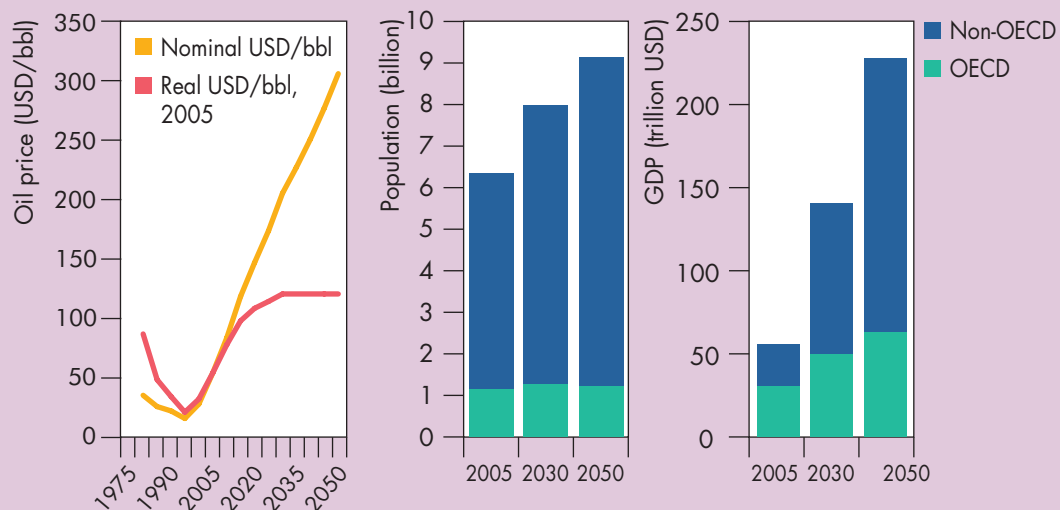
scenario is used mainly to enable analysis of the potential impact on electricity generation around the world.

Box 1.2 ► Population, GDP and oil price assumptions

Population and GDP growth trends assumed in this publication match the projections used in WEO 2008. The current global economic downturn is not fully reflected in these GDP projections. This will cause near-term projections, e.g. for 2010, to diverge from the assumed trend lines. But over the long term, e.g. to 2050, the impacts are likely to be minor assuming that the world economic system returns to its projected growth track within a few years. In this case, the downturn will have led to a delay in GDP growth, pushing back by up to several years the date when future GDP reaches a given level in each region.

The future oil prices assumed in this analysis are also based on WEO 2008, rising from USD 100/bbl in the near term, after the recovery from the current economic downturn, to USD 120/bbl in 2030, in 2006 real USD. It is assumed that prices stay at that level in real terms through to 2050, although this implies a nominal oil price of over USD 300/bbl in that year. This price forms the basis for the transport and efficiency trends in the Baseline scenario. But for the analysis of technologies, fuels and policies, a lower oil price of USD 60/bbl throughout the period to 2050 is also considered. Such a lower price might occur particularly in a world that moves toward significant reductions in oil use, as in the BLUE scenarios.

Figure 1.7 ► Population, GDP and oil price assumptions for 2005, 2030 and 2050 for the Baseline scenario



Sources: IEA (2008b); United Nations (2008); OECD (2008).

Key point

Exogenous assumptions for key parameters are consistent with other IEA publications.

The BLUE FCV Success case from *ETP 2008* is not further analysed in this publication. Although further work has been done on EVs, no additional analysis has been undertaken for a transition to a FCV future since *ETP 2008*. Additional FCV analysis may be undertaken for *ETP 2010*. However, FCVs play an important part in achieving the outcomes of the BLUE Map scenario, and revised FCV and hydrogen fuel cost estimates are presented in Chapters 2 and 3.

In addition, some results are presented for scenarios that have been run in combination, in particular the BLUE Shifts scenario together with the BLUE Map scenario (called BLUE Map/Shifts). This provides an indication of the potential for energy savings and CO₂ reductions if very aggressive efforts are made in terms of future technologies and fuels, and in the way in which people travel and freight is moved. This combination results in greater reductions in transport fuel use and CO₂ emissions than either scenario separately.

The BLUE Map scenario is also analysed in combination with the assumptions made in the High Baseline scenario, designed to reflect the impact of technology and fuel measures against a higher rate of growth in transport activity through to 2050. The BLUE Shifts scenario is not combined with the High Baseline scenario since by definition it implies a move towards relatively low travel levels. Achieving the outcomes assumed in the BLUE Shifts scenario will be much more difficult if the underlying trends are headed toward the outcomes envisaged in the High Baseline scenario rather than those in the Baseline scenario.

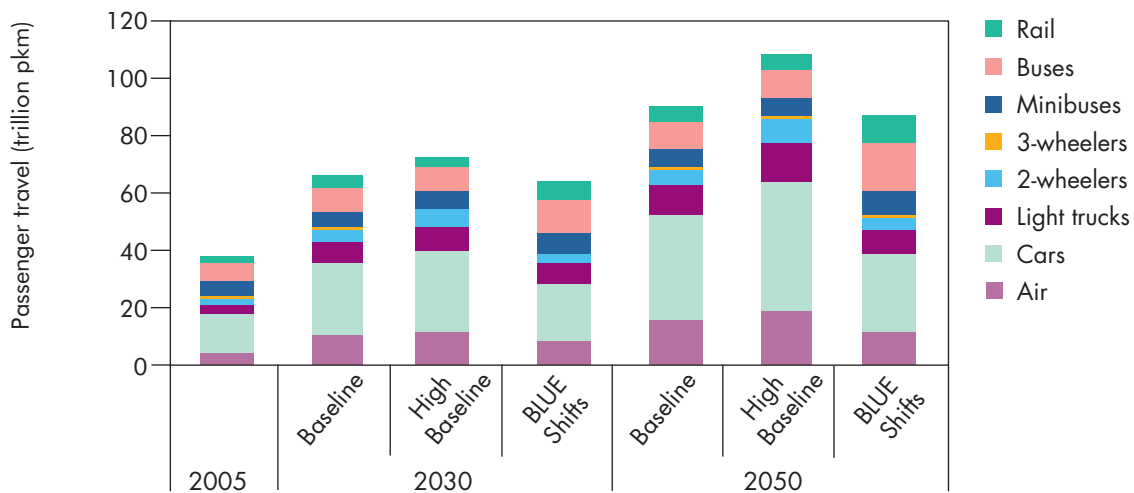
Scenario results

The overall picture that emerges from the projections and scenarios is that OECD countries are nearing or have reached saturation levels in many aspects of travel, whereas non-OECD countries – and especially rapidly developing countries such as China and India – are likely to continue to experience strong growth rates into the future through to at least 2050. In OECD countries, the biggest increases in travel appear likely to come from long-distance travel, mainly by air. In non-OECD countries, passenger LDV ownership and motorised two-wheeler travel are likely to grow rapidly in the decades to come, although two-wheeler travel may eventually give way to passenger LDV travel as countries become richer. Freight movement, especially trucking, is also likely to grow rapidly in non-OECD regions. In all regions of the world, international shipping and aviation are likely to increase quickly.

In the Baseline scenario, travel growth will be triggered by strong growth in the number of households around the world that gain access to individual motorised transport modes. This will, in turn, lead to a rise in average travel speeds and increased travel distances, and reinforce land-use changes such as suburbanisation. Increasing wealth will also trigger more frequent and longer distance leisure-related trips, in particular through increased tourism generating considerable amounts of long-distance travel. Figure 1.8 shows the projected evolution of motorised passenger mobility by mode to 2050 for the Baseline and High Baseline scenarios, as well as the effect of the modal shift policies adopted in the BLUE Shifts scenario. Estimated motorised passenger travel was about 40 trillion kilometres in 2005. This is projected to double by 2050 in the Baseline scenario and to increase by 150% in the High Baseline scenario.

The BLUE Shifts scenario projects a different sort of future travel. Although it reduces overall travel only slightly on a worldwide basis compared to the Baseline scenario, the composition of that travel changes significantly, with much greater travel shares being undertaken by bus and rail, the most efficient travel modes. It is assumed that strong investments in, and expansion of, bus and rail services in the developing world induce a significant increase in motorised travel. For most non-OECD countries, travel by bus and rail is so much higher in the BLUE Shifts scenario than in the Baseline scenario that it results in net increases in the total amount of travel worldwide, more than offsetting decreases in travel in OECD regions where the use of telematics and changes in land use result in a net reduction in travel compared to the Baseline scenario.

Figure 1.8 ▶ Passenger mobility by mode, year and scenario



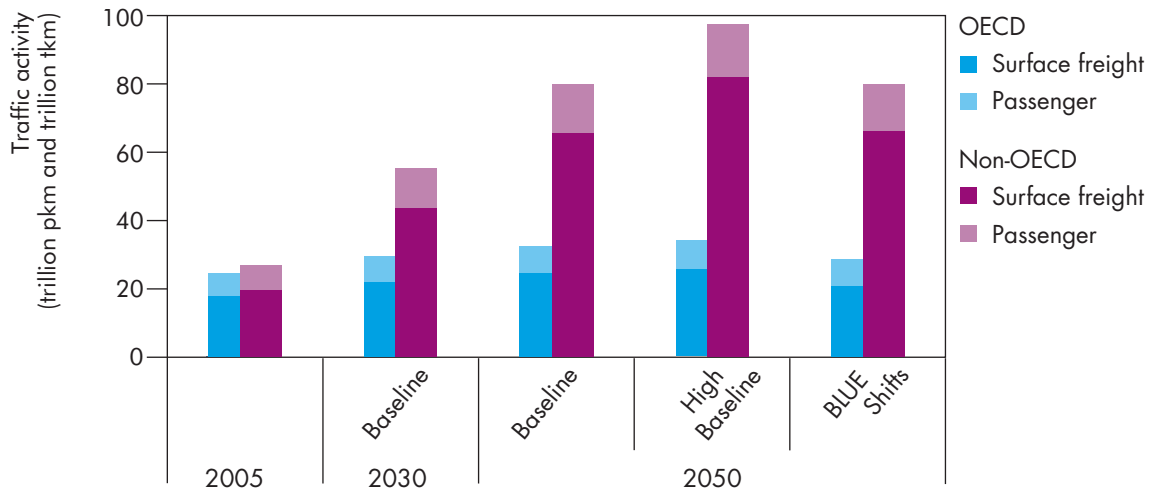
Key point

The BLUE Shifts scenario suggests it could be possible to significantly reduce reliance on passenger LDVs.

The strong link between GDP and freight traffic activity continues in the future in the Baseline scenario. As a result, non-OECD countries are expected to show the biggest growth in freight surface transport. The MoMo does not currently enable the projection for shipping and air goods transport. Figure 1.9 shows the passenger and freight traffic activities for OECD and non-OECD countries highlighting the extent to which non-OECD countries' transport growth is expected to dominate worldwide growth in the future. Non-OECD traffic activity in 2050 in the Baseline and BLUE Shifts scenarios are the same because there is no reduction in overall mobility, only a shift to mass transit modes.

Energy and GHG intensity

The future energy intensities of different transport modes will play an important role in determining overall energy use and CO₂ emissions. Figure 1.11 shows possible evolutions for passenger and freight modes, for a range of different scenarios,

Figure 1.9 ► Mobility split by type of transport, OECD and non-OECD**Key point**

Non-OECD passenger kilometres are expected to grow the most in all scenarios.

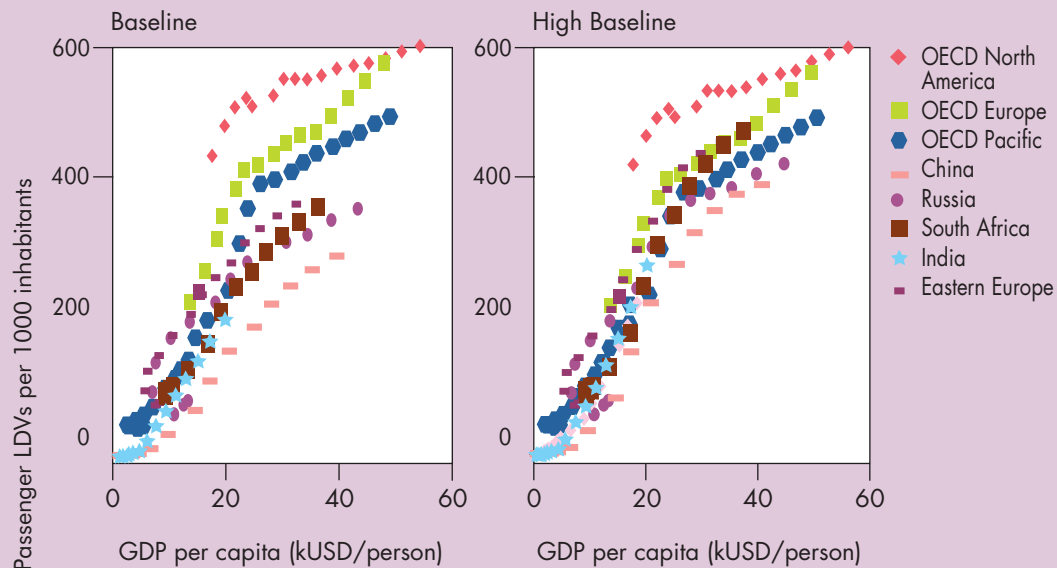
Box 1.3 ► Passenger LDV ownership projections

Passenger LDV ownership rates play a significant part in determining future travel and energy use. Historically, there has been a strong correlation between income levels and the rate of passenger LDV ownership. This typically follows an S-shaped curve that becomes steep when per capita income reaches about USD 5 000. LDV ownership rises rapidly with income above this level, until income reaches a higher level at which LDV ownership saturates. Experts have used such a curve to model rates of LDV ownership against GDP per capita, reflecting such factors as income distribution, road infrastructure development, the urbanisation of the population and the cost of LDV ownership relative to income (Dargay, 1999).

The IEA Baseline and High Baseline scenarios reflect different assumptions as to the way in which the income/LDV ownership relationship may play out. In the High Baseline scenario, growth in LDV ownership in non-OECD countries is assumed to follow broadly the pattern in which passenger LDV ownership has grown historically in OECD countries. In the Baseline scenario, LDV ownership in non-OECD countries is lower than it has historically been in the OECD for the same level of income, and levels for ownership saturate at a lower level. There are a number of reasons why this may occur. Income growth in some non-OECD countries, such as China, may reflect much greater income disparities than in most OECD countries in the past. Some regions are likely to reach higher levels of urbanisation with more wealth concentration in urban areas and, hence, less need for personalised travel. In South and East Asia, ownership of motorised two-wheelers is already very high; this may dampen growth in the ownership of LDVs. A relatively slower rate of road infrastructure development could also inhibit the rate of increase in LDV ownership, for example if severe traffic congestion develops.

Figure 1.10 shows the impact of the different ownership assumptions in the two scenarios by region. By 2050, passenger LDV ownership levels in the Baseline scenario reach about 350 LDVs per 1 000 people in Korea, Russia, Eastern Europe, Latin America and South Africa, and about 250 LDVs per 1 000 people in China, India and South-East Asia. The overall difference in the total number of LDVs in the two scenarios is very significant: in the Baseline scenario, world LDV stock reaches about 2.1 billion vehicles in 2050, whereas in the High Baseline scenario it reaches 2.6 billion. Including light commercial trucks (similar in size to large LDVs), High Baseline stocks reach almost 3 billion.

Figure 1.10 ▶ Passenger LDV ownership rates and GDP per capita in the Baseline and High Baseline scenarios, selected regions



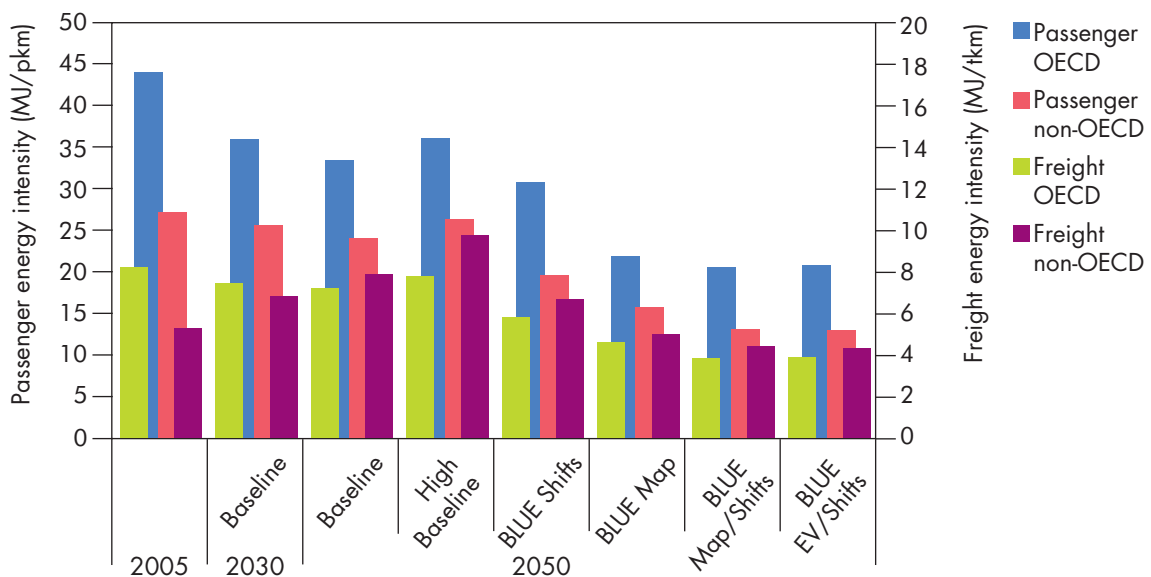
Key point

The High Baseline scenario explores the possibility of doubling the passenger LDV ownership in non-OECD Asian countries, relative to the Baseline.

based on averages for OECD and non-OECD countries. In all of these scenarios, transport efficiency improves over time but at differing rates. In 2005, average energy intensities in OECD countries are considerably higher than in non-OECD, particularly for passenger modes. This is due to the modal mix and to higher load factors, *i.e.* on average there being more passengers per vehicle in the developing world. In the Baseline scenario, OECD countries' transport efficiencies improve significantly so that, by 2050, OECD energy intensities are close to those in non-OECD regions. Over the same period, energy intensity in non-OECD countries improves only slightly or even declines, for example for freight. In the High Baseline scenario, efficiency decreases in all modes due to assumptions about lower load factors and slower improvements in the technical efficiency of different vehicle types.

In the BLUE Shifts scenario, modal shifts toward more efficient modes (i.e. bus and rail for passenger transport, and rail for freight transport) help to reduce average energy intensities considerably beyond the levels in the Baseline scenario. In the BLUE Map scenario, strong technical efficiency improvements across modes and operational improvements in modes such as trucking result in average energy intensities reaching an even lower level, on the order of half of their 2005 levels. Combining the assumptions of the BLUE Shifts scenario with those of the BLUE Map scenario achieves both a better mix of modes and more technically efficient modes. This results in an even lower level of energy intensities, although the effect is less than proportionate since, once the technical efficiency of all modes is much improved, the benefit of shifting modes is reduced.

Figure 1.11 ▶ Vehicle energy intensity evolution for passenger and freight, OECD and non-OECD

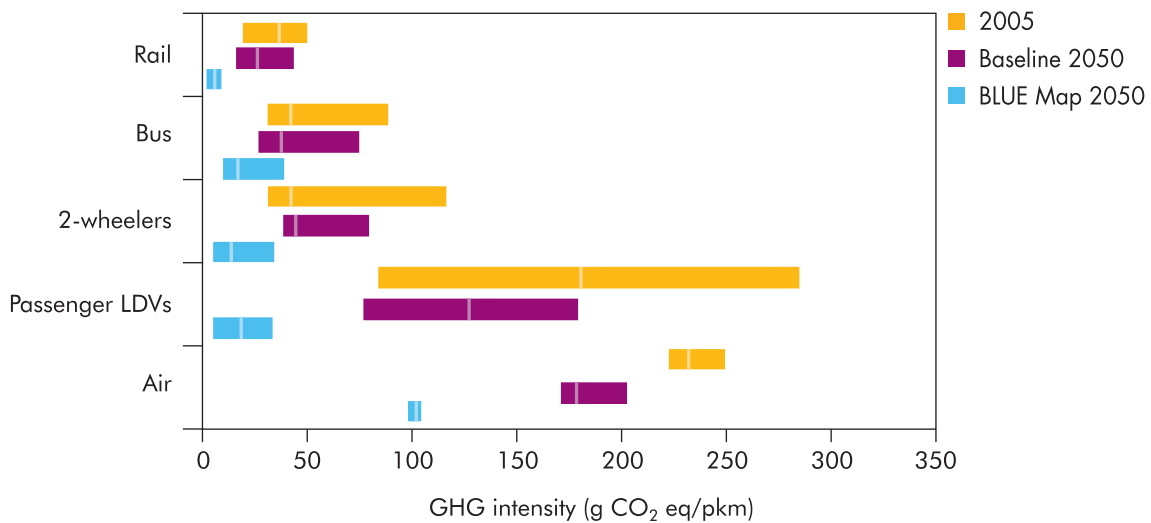


Key point

In all regions, passenger and freight energy intensity in 2050 in BLUE Map is far better than in the Baseline.

GHG intensity by passenger transport mode in the Baseline and BLUE Map scenarios is shown in Figure 1.12. Given the relatively high oil price assumptions in WEO 2008 and existing policies such as the fuel economy standards in many OECD countries, the GHG intensity of LDVs decreases by 30% between 2005 and 2050 in the Baseline scenario. This is a substantial improvement. The GHG intensity of all other modes (except motorised two-wheelers) decreases as well, typically by about 15%. In the BLUE Map scenario, all modes reduce their GHG intensity by at least 50% by 2050. In the BLUE Map scenario and the BLUE EV Success scenario, FCVs, EVs, two-wheelers and rail help to cut modal CO₂ emissions by 80% or more, due to the widespread availability of very low-carbon hydrogen and/or electricity in these scenarios by 2050.

Figure 1.12 ► GHG intensity of passenger transport in 2005 and 2050, Baseline and BLUE Map scenarios



Note: The clear line indicates world average, the bar representing MoMo regions' discrepancy.

Key point

The CO₂ intensity of all modes improves dramatically by 2050 in BLUE, with all but air travel reaching below 50 grams of CO₂ per kilometre of passenger travel.

Energy use scenarios

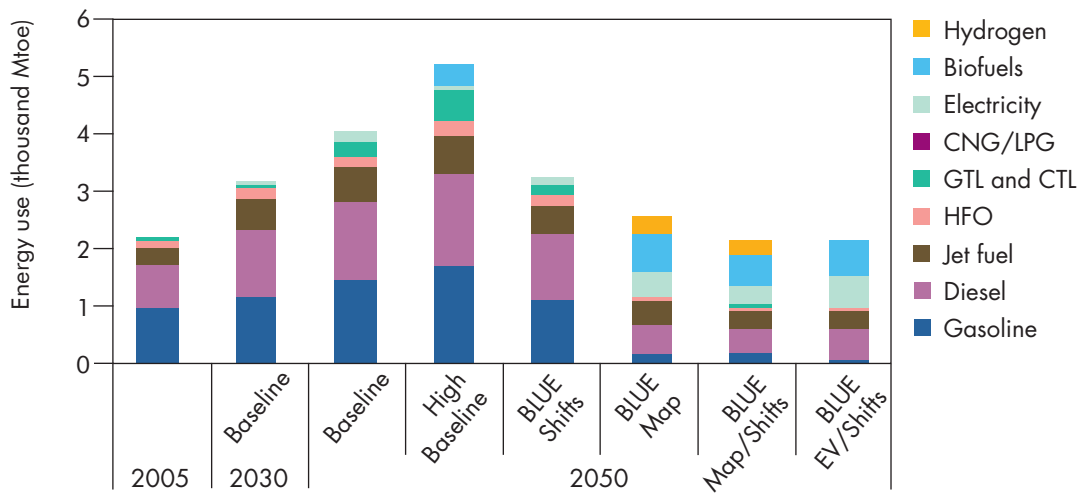
The net impacts on energy use in each of the scenarios are shown in Figure 1.13. In the Baseline scenario, and even more in the High Baseline scenario, energy use grows substantially to 2050 as efficiency improvements are outweighed by growth in transport activity. In the BLUE Shifts scenario, energy use in 2050 is around the same level as in the Baseline scenario in 2030, suggesting a degree of stabilisation. In the BLUE Map scenario, energy use returns to the 2005 level. When the BLUE Shifts scenario is combined with the BLUE Map or with the BLUE EV Success scenarios, energy use drops to a level lower than that in 2005.

There are also important differences between scenarios in the composition of fuels used. In the Baseline and High Baseline scenarios, little non-petroleum fuel is used even in 2050, although in the High Baseline scenario a substantial amount both of synthetic fossil fuels and biofuels is used. As a result, fossil fuel use increases by 50% in the Baseline scenario and doubles in the High Baseline scenario. The High Baseline scenario would require an increase in 2050 of more than 80 Mbd in liquid fuels just for the transport sector, which is likely to be very challenging from a supply perspective.

By contrast, in the BLUE Map scenario, the need for fossil energy for transport halves, reflecting very large shifts to low CO₂ alternative fuels such as low CO₂ electricity and hydrogen, and advanced biofuels. More details on the use of different fuels for transport can be found in Chapter 2. In the BLUE scenarios, most conventional gasoline and diesel powered LDVs have disappeared by

2050, being replaced largely by hydrogen and electricity powered vehicles. But for heavier, long-distance modes (such as trucks, planes and ships), diesel fuel, jet fuel and heavy fuel oil or marine diesel still dominate. Biofuels, which are mainly biodiesel rather than ethanol in 2050, play an important role in displacing liquid fossil fuels in these long-distance modes. Biofuels reach about 33% of total transport fuel use in BLUE Map in 2050, including about 30% of truck, aircraft and shipping fuel and 40% of LDV fuel. For LDVs, nearly all the rest is electricity and hydrogen; for trucks, ships and aircraft, most of the rest remains petroleum fuel.

Figure 1.13 ► Evolution of energy use by fuel type, worldwide

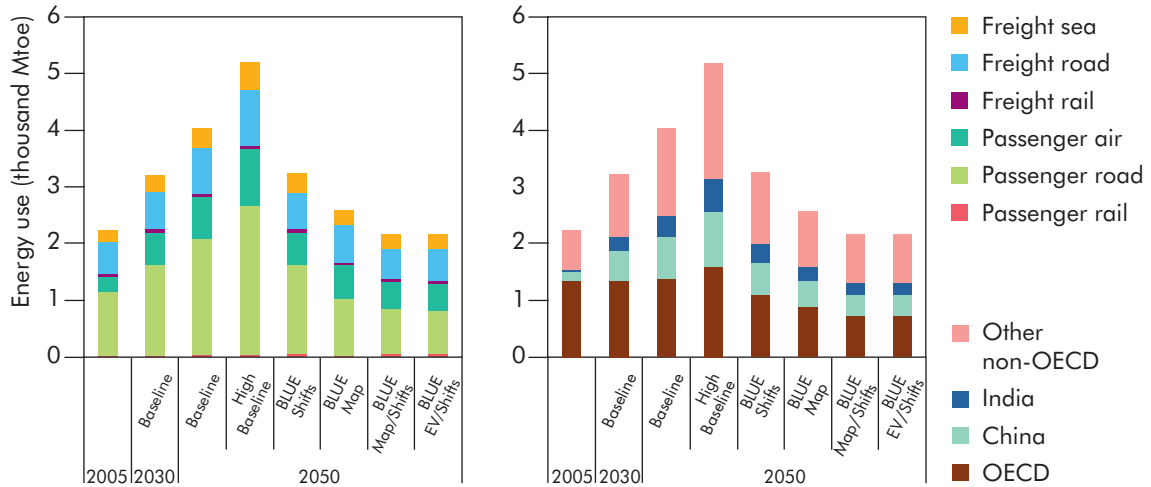


Key point

The BLUE scenarios cut energy use by close to half compared to the Baseline in 2050, and also cut fossil fuel to less than 50% of energy use.

Figure 1.14 shows energy use from the modal and regional perspectives for each scenario. Passenger travel accounts for about two-thirds of total transport energy use in 2005; this proportion does not change significantly in the future in either the Baseline or High Baseline scenarios. But in the BLUE scenarios, particularly in the BLUE Map scenario, more energy saving occurs in passenger modes than freight modes. This is due mainly to LDVs, which achieve the biggest overall efficiency gains as a result of the increase in EVs or FCVs. The overall balance of energy use shifts toward freight.

In the BLUE Shifts scenario, the share of bus and rail is substantially increased. Rail transport volumes, for example, double between 2005 and 2050, going from 18% to 23% of the total traffic activity. But bus and rail's share of energy use remains relatively low, especially that of rail. No data is available regarding air freight. Although the tonnage sent by air is low, the value of the goods sent is high (Air France, 2009). Dedicated air haulage of freight is increasing; thus, will be important to be able to track this growth in the future.

Figure 1.14 ▶ Energy use by type of transportation and by region**Key point**

Passenger travel accounts for about two-thirds of total transport energy use in the Baseline and High Baseline scenarios, however in the BLUE scenarios more energy saving occurs in passenger modes than freight modes. Regionally, most of the energy use growth occurs in the non-OECD.

In the Baseline and High Baseline scenarios, nearly all growth is in non-OECD regions. In the BLUE Shifts scenario, energy use in OECD countries drops significantly below its 2005 level, although energy use in non-OECD countries still grows significantly. But as shown in Chapter 5, the level of travel and energy use per capita remains much higher in OECD than non-OECD countries. The BLUE Shifts scenario assumes that travel in OECD and non-OECD countries will converge sometime after 2050.

Projections for GHG emissions

In the transport sector, CO₂ is the main GHG contributor. Other GHGs, such as N₂O and CH₄, are also taken into account in the modelling, but the focus is mainly on CO₂. In the BLUE scenarios, energy use in 2050 returns to 2005 levels or slightly lower. If the energy mix stays constant, as in the BLUE Shifts scenario, CO₂-equivalent GHGs would show the same trajectories. A switch to lower CO₂ energy sources, as in the BLUE Map and BLUE EV scenarios, results in greater CO₂ reductions.

The CO₂ intensity of the fuels in the BLUE Map and BLUE EV scenarios is dependent on the manner in which they are produced. For example, the electricity generation mix in the BLUE Map scenario becomes progressively less CO₂ intensive over time as fossil fuel generation is replaced by nuclear and renewable generation, and by biofuels. By 2050 it is nearly completely decarbonised. If this does not happen, then the CO₂ benefits of shifting to EVs will be far less than shown here. Table 1.3 shows the contribution of different primary energy sources to electricity generation for each scenario. This is covered in more detail in Chapter 2.

Table 1.3 ► Electricity share – percent of generation by major energy source, year and scenario

	Electricity share (% of electricity generation)	Baseline			BLUE Map	
		2005	2030	2050	2030	2050
OECD	Fossil	59%	61%	68%	6%	0%
	Fossil + CCS	0%	1%	0%	14%	17%
	Nuclear	23%	16%	13%	31%	33%
	Renewable (including biomass)	17%	22%	18%	49%	50%
Non-OECD	Fossil	76%	78%	82%	48%	7%
	Fossil + CCS	0%	0%	0%	9%	30%
	Nuclear	2%	3%	4%	10%	17%
	Renewable (including biomass)	21%	19%	15%	33%	46%
World average	Fossil	66%	70%	76%	31%	4%
	Fossil + CCS	0%	1%	0%	11%	26%
	Nuclear	15%	9%	8%	20%	23%
	Renewable (including biomass)	19%	20%	16%	38%	47%

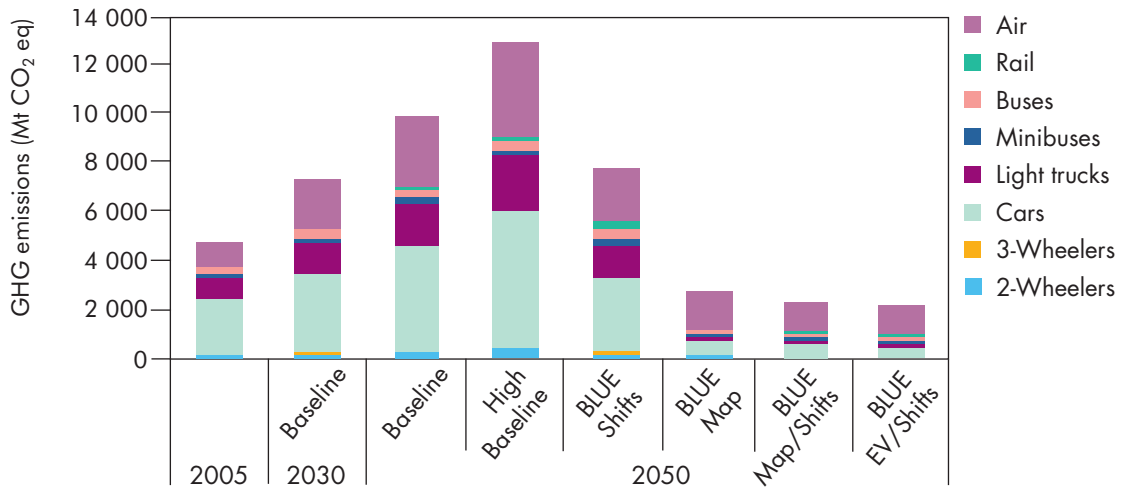
Source: IEA Mobility Model database and scenarios, based on IEA (2008a) scenarios.

Figure 1.15 shows passenger mobility GHG emissions by mode and scenario, highlighting a wide range of possible futures. In the Baseline and High Baseline scenarios, aviation becomes one of the largest transport GHG emitters in 2050. In percentage terms, this is even more pronounced in the BLUE Map scenario as emissions from LDVs are reduced by the switch to non-fossil energy sources. More details on the air sector's technology pathways can be found in Chapter 7.

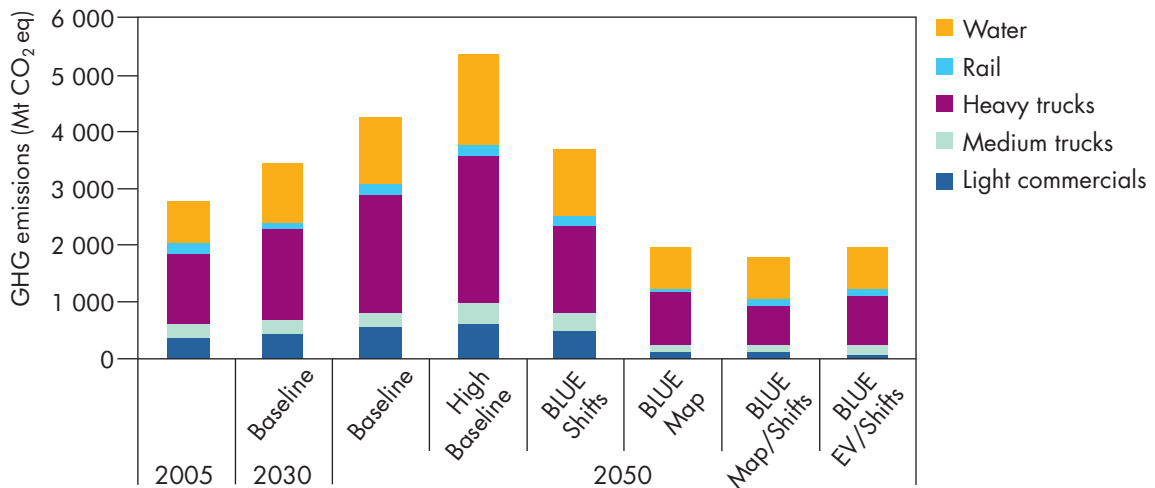
Surface freight is discussed in detail in Chapter 6. Heavy trucks will continue to emit more GHGs than other freight modes, with a particularly high share of about 60% in the High Baseline scenario. Significant efficiency improvements in all trucks are expected. Some shift to electricity or the use of fuel cells for light and medium commercial trucks is implicit in the BLUE Map scenario. But only a very small amount of such shifting is assumed for heavy trucks, with diesel engines remaining dominant until at least 2050. Heavy trucks often travel very long distances and refuelling needs to be quick. This limits the options for alternative fuels.

As shown in Figure 1.16, water-borne transport (including national and international maritime transport) also represents an increasing share of emissions. As with heavy trucks, the options for CO₂ reductions in the future are limited. But there appear to be important efficiency improvement options for ships. Shipping is covered in Chapter 8.

The split between well-to-tank and tank-to-wheel CO₂-equivalent GHG emissions varies. Until 2050, well-to-tank emissions account for anywhere between 7% and 20% of the total well-to-wheel GHG emissions in the scenarios considered. As

Figure 1.15 ▶ Passenger mobility GHG emissions by mode**Key point**

By 2050 in BLUE Map, GHG emissions reach extremely low levels except for in air travel.

Figure 1.16 ▶ Freight mobility GHG emissions by mode**Key point**

For freight transport, emissions are cut by half in BLUE Map in 2050 compared to the Baseline scenario, but maritime transport and trucking continue to emit significant GHGs.

vehicles become more efficient, the relative importance of upstream emissions may increase in some cases. In particular, zero-emission vehicle technologies such as FCVs and EVs shift CO₂ emissions from tank-to-wheel to well-to-tank. But as shown in ETP 2008, the decarbonisation of the energy production process may, in many cases, be less expensive in terms of costs per tonne of CO₂ saved than reducing CO₂ emissions from vehicles themselves.

The relative contributions to be made by OECD and non-OECD countries in reducing CO₂ emissions are controversial and are the subject of on-going negotiations. The contributions in these scenarios follow the reductions in fossil energy use by region, as a result of which larger reductions will come from OECD countries than from non-OECD countries. However those reductions are achieved, joint implementation programmes and carbon credit trading systems will be needed to allow an equitable distribution of effort and the lowest cost options to be given priority wherever they are found. In transport, vehicle types and technologies are converging around the world. This may mean that relative costs become increasingly similar across all regions.

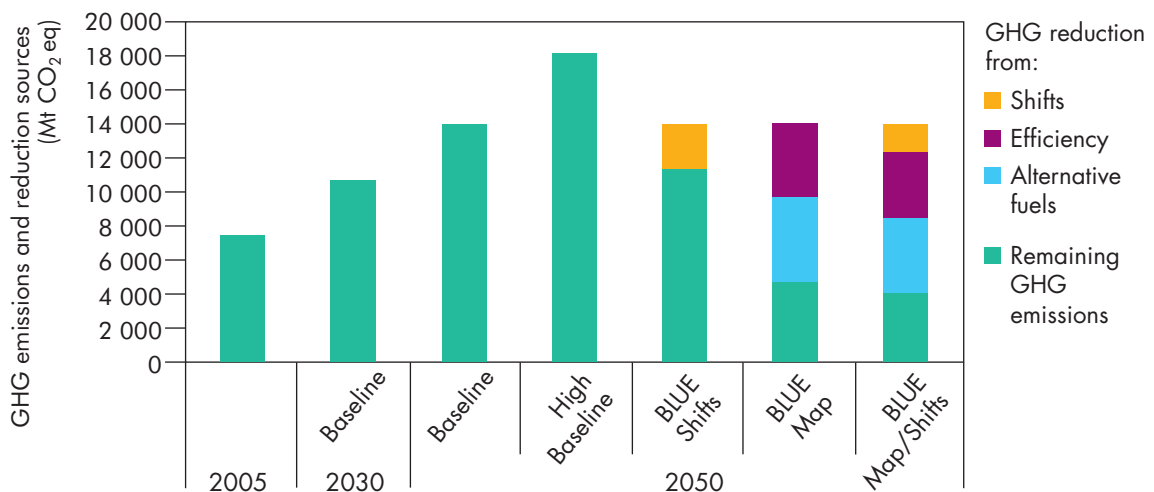
Sources of GHG reduction

Technology and modal shift policies will be needed to achieve the strong reductions in GHGs depicted in the more challenging of these scenarios. Chapter 4, for example, focuses on the role of vehicle efficiency policies in helping to achieve potential improvements. The reductions achieved by different approaches will depend both on relative costs and on the ability of governments to implement effective policies relating to travel, efficiency and fuel use.

GHG reductions for transport will come from three main sources (Figure 1.17):

- **Modal shifts** in urban short-distance travel and in long-distance travel from, for example, greater use of high-speed trains.
- **Efficiency** from new technologies that reduce the energy use of vehicles and from operational improvements for truck transport management.
- **Alternative fuels** that allow vehicles to emit less CO₂ per unit of energy used, for example, through the use of less carbon-intensive energy sources.

Figure 1.17 ► Sources of GHG emission reduction, transport sector



Key point

Modal shift, efficiency and alternative fuels all play significant roles in cutting GHGs by 2050.

As shown in Figure 1.17, modal shift can provide over 2 Gt of GHG reductions relative to the Baseline scenario, excluding non-motorised transport. Modal shift can provide reductions of over 6 Gt from the High Baseline scenario as evidenced by the far lower levels of passenger LDV and air travel in the BLUE Shifts scenario. The basis for the shifts analysis is described in Chapter 5 for passenger travel and Chapter 6 for freight travel.

In the BLUE Map scenario, strong efficiency improvements and shifts to low CO₂ fuels provide CO₂ reductions of the order of 4.5 Gt each, relative to the Baseline scenario in 2050. This is a two-thirds reduction and is also about 40% below 2005 levels. This is more than was achieved for transport in *ETP 2008* and mainly reflects slightly slower growth in the Baseline scenario, though it also reflects minor adjustments such as slightly better EV efficiency than was assumed in *ETP 2008*.

When the BLUE Map scenario is combined with the BLUE Shifts scenario, efficiency, modal shifts and alternative low CO₂ fuels all play an important part in achieving a reduction of about 10 Gt of CO₂ compared to the Baseline scenario in 2050, and almost a 50% reduction compared to 2005. But, as individual effects combine, each element contributes slightly less in this scenario than in the two scenarios run separately. For example, strong decarbonisation across all modes in the BLUE Map scenario reduces the CO₂ intensity differentials between modes, so modal shift provides somewhat less benefit in cutting CO₂. Conversely, with lower levels of travel in the BLUE Shifts scenario, the efficiency gains and lower CO₂ fuels in the BLUE Map scenario provide slightly smaller CO₂ reductions.

Ultimately, as it is not clear that all of these sources of CO₂ reduction can be achieved at the levels described here, and as there appear to be low-cost opportunities in all three areas (as shown in later chapters), all of them should be pursued vigorously. If for some reason one aspect plays a reduced role, then others will automatically provide larger CO₂ reductions – the converse of the synergistic aspects outlined above.

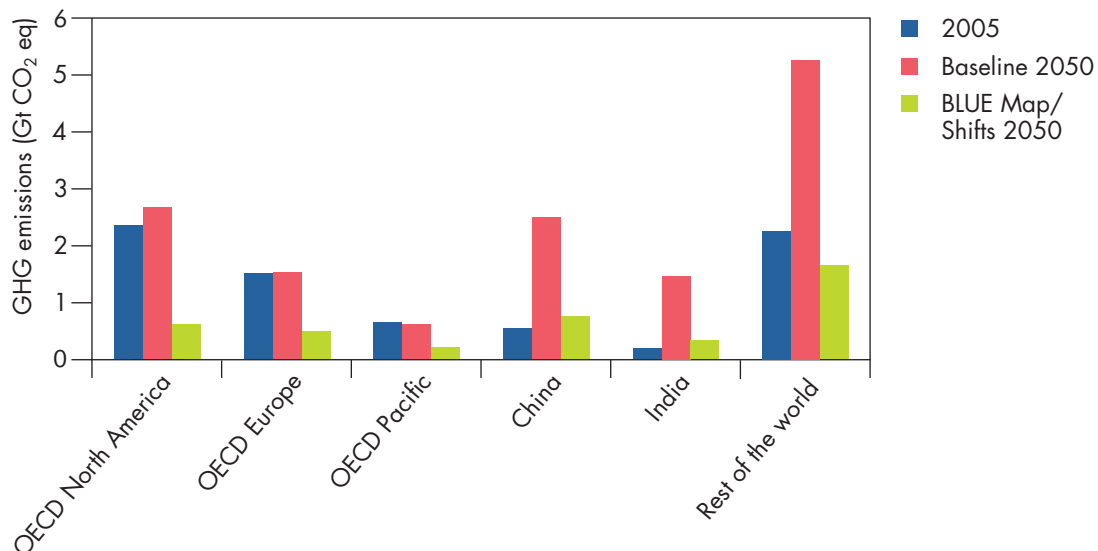
The scenarios are conceived with the aim of achieving the maximum CO₂ reductions at minimum cost, particularly through the deployment of technology over time. However, the results shown do not derive from an automated modelling tool designed for a cost minimisation approach. The analysis combines information on technological potentials and costs, considerations of different circumstances affecting global macro-regions, and – to some extent – a back-casting method. This combination of analytical approaches helps deal with important uncertainties that are extremely difficult to approach in a pure cost minimisation modelling tool while working on the global scale. It allows figuring out where important changes need to occur, and the extent to which they can contribute to energy and CO₂ emission savings.

The scenarios are not linked to regional targets, but estimates relative to the implications for CO₂ reductions by region can be derived in each of them. Figure 1.18 shows the transport CO₂ emissions for 2005 and in 2050 in the Baseline and BLUE Map/Shifts scenario for six major countries and regions. In all regions, the reduction in CO₂ emissions between the Baseline and BLUE Map/Shifts scenario in 2050 is more than 50%. But compared to 2005 emission levels, OECD regions achieve far bigger reductions than non-OECD regions, while India

and China show increases. On a per capita basis, the starting points for OECD countries are, of course, far higher than those for non-OECD countries, so this result is not surprising.

As shown in Chapter 5, travel levels per capita by 2050 are beginning to converge across regions, especially for urban travel. Non-urban travel levels in OECD countries remain far higher than those in non-OECD countries. The use of alternative fuels and advanced technology vehicles also becomes more similar across regions, after a five-to-ten year head start in OECD regions in most cases. So the BLUE Map/Shifts levels of CO₂ in 2050 reflect not only much more sustainable travel in all regions, but also travel patterns that are more similar across regions than they are either today or in the Baseline scenario.

Figure 1.18 ▶ Transport GHG emissions by region and scenario, 2005 and 2050



Key point

All regions achieve deep CO₂ reductions by 2050 in BLUE Map/Shifts, compared to the Baseline scenario.

Chapter 2 TRANSPORT FUELS

Key findings

- ▶ Transport used 2 231 Mtoe of energy worldwide in 2006, with by far the highest levels of use in OECD North America and Europe. Fuel use worldwide is expected to increase by 80% between 2005 and 2050 in the Baseline scenario and to more than double in the High Baseline scenario.
- ▶ Transport remains heavily dominated by petroleum fuels in all world regions. Biofuels (ethanol and biodiesel), liquefied petroleum gas (LPG), compressed natural gas (CNG) and electricity play a small role in a few regions. In the Baseline scenario, the dominance of petroleum fuel continues. In the High Baseline scenario, synthetic fuels (such as gas and coal-to-liquid fuels) play an increasing role after 2030 as part of meeting the higher fuel demand, and account for 10% of total transport fuel in 2050.
- ▶ In the BLUE Map scenario, total transport fuel use returns close to 2005 levels by 2050, and the use of very low CO₂ fuels, particularly hydrogen, electricity, and second-generation biofuels, increases significantly. By 2050, these fuels account for more than half of all the fuel used in transport. Total fuel use drops to slightly below 2005 when the assumptions in the BLUE Map scenario are combined with those in the BLUE Shifts scenario, reflecting modal shifts and slower travel growth. In the BLUE EV scenario, electricity use mainly in electric and plug-in hybrid LDVs accounts for one-quarter of transport fuel use and most of LDV fuel use by 2050.
- ▶ Most regions do not currently generate enough low CO₂ electricity to enable EVs and PHEVs to contribute significantly to large CO₂ reductions. In the Baseline scenario, this remains the case through 2050. On this basis, vehicle electrification seems unlikely to be a cost-effective route to significant CO₂ reductions in the absence of strong efforts to decarbonise electricity generation. In the BLUE scenarios, this decarbonisation occurs so that EVs provide near-zero CO₂ transportation in all regions by 2050. In the BLUE Map scenario, the global stock of EVs rises to 470 million by 2050, resulting in around 2 Gt of CO₂ reduction in that year. In the BLUE EV scenario, the number of EVs and the level of savings both nearly double.
- ▶ A new analysis of fuel costs indicates that in the near term and with oil prices of around USD 60/bbl, most alternative fuels will be more expensive than gasoline or diesel, with the exception of cane ethanol in Brazil. With oil prices at around USD 120/bbl, some additional fuels become competitive, including gas-to-liquids (GTL), coal-to-liquids (CTL) and hydrogen produced from natural gas. In the longer term, with higher oil prices and cost reductions through research, development and demonstration (RD&D) and technology learning, many fuels may become cost-competitive with petroleum fuels or close to it. These include ligno-cellulosic ethanol, biomass-to-liquids (BTL) and hydrogen derived from biomass.

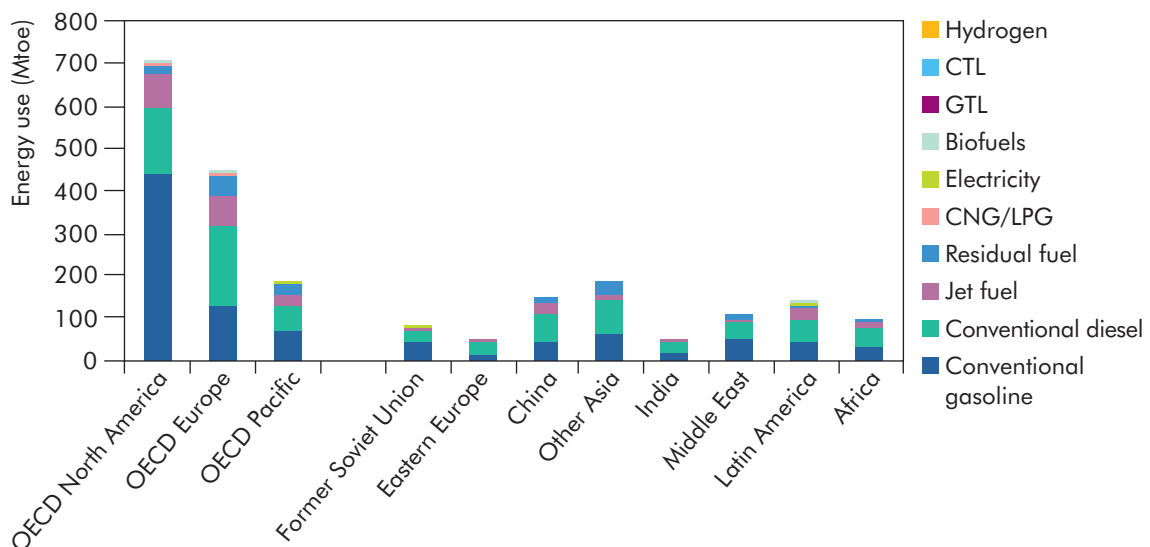
- ▶ Given the potential for large GHG reductions from electricity, hydrogen and biofuels, the cost analysis suggests that these fuels, combined with various feedstocks, may eventually offer relatively low-to-moderate cost options for reducing GHG emissions, especially as oil prices rise. These may need time to develop, perhaps more time than making efficiency improvements and achieving some modal shifts, but eventually these fuels should be capable of providing substantial CO₂ reductions for under USD 100/tonne.

Current status and trends

Transport can be powered in many different ways. Fuel choices have an important impact on the way in which scarce resources are used, on energy security, and on GHG and pollutant emissions.

Transport fuel use worldwide is currently dominated by petroleum, with over 95% of fuel being either gasoline or distillate fuels such as diesel, kerosene or jet fuel. However, some countries use significant amounts of CNG or LPG, a mix primarily of propane and butane. Some countries and regions use far more fuel than others (Figure 2.1), as a function of greater levels of passenger travel and goods transport, as well as of the fuel efficiency of that transport.

Figure 2.1 ▶ Fuel use by region, 2005



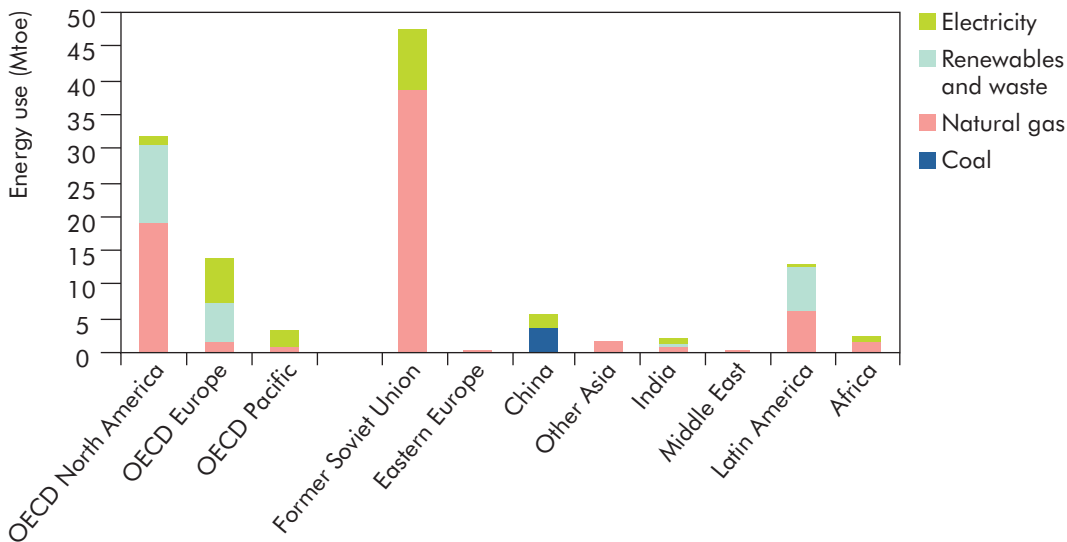
Source: IEA Mobility Model.

Key point

In 2005, most transportation fuel use occurred in OECD regions.

In some regions, non-petroleum fuels play an increasingly significant role (Figure 2.2). Countries in OECD North America (especially the United States) and in Latin America (especially Brazil) are rapidly increasing their use of biofuels, mostly blended with conventional petroleum fuels. CNG and LPG play an important role in some parts of OECD Europe, Latin America and OECD North America. Electricity is used extensively to fuel passenger rail systems in Europe and parts of Asia. GTL and CTL are not significantly used, except CTL in South Africa. Hydrogen is not currently used in any great volume as a transport fuel anywhere.

Figure 2.2 ▶ Non-petroleum fuel use by region, 2005



Key point

Use of non-petroleum fuels is marginal and usually depends on local resource availability.

Future fuel scenarios

The Energy Technology Perspectives 2008, *ETP 2008* (IEA, 2008a) scenarios project a wide range of transport fuel demand patterns over the period to 2050.

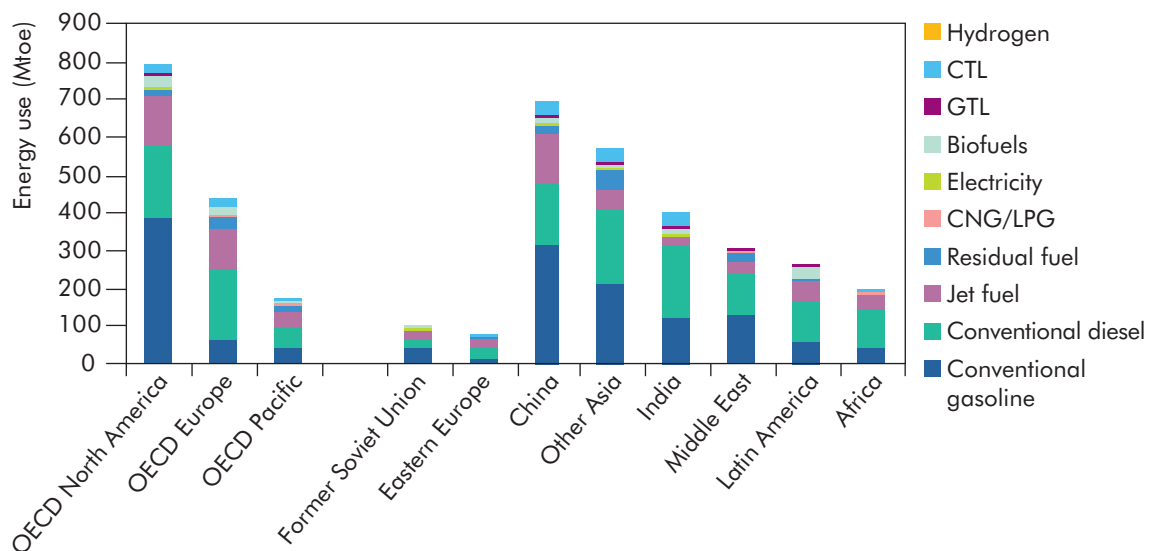
The scenarios in which CO₂ emissions are not specifically constrained, i.e. the Baseline and High Baseline, project far higher total fuel requirements in 2050 than 2005, with little change in the share of conventional gasoline and diesel fuel. In the Baseline scenario, over 4 000 billion litres (gasoline equivalent) of fuel is used in 2050, 95% of which is fossil-fuel based. In the High Baseline, this is over 6 000 billion litres. These scenarios are characterised by continuing robust growth in transport volumes, offset by significant fuel efficiency gains, but little shifting to non-fossil fuels. Synthetic fuels, such as CTL and GTL, are assumed to grow rapidly after 2030 as constraints in the potential growth of conventional petroleum fuels begin to increase, making synthetic fuels more competitive. Given their relatively high CO₂ intensity, this increases CO₂ emissions. This increase is partly offset by the increased use of first-generation biofuels such as grain ethanol and oil-seed based biodiesel.

In the BLUE Shifts scenario in 2050, travel growth rates are lower than in the Baseline scenario, and travel shifts somewhat from more energy intensive modes (LDVs, trucking, air travel) to less energy intensive modes (rail, bus). As a result, overall fuel demand declines by about 20% in 2050 compared to the Baseline, but the mix of fuels does not change substantially.

The BLUE Map scenario envisages travel patterns similar to those in the Baseline scenario but with strong efficiency improvements cutting fuel demand and a switch to low CO₂ biofuels, electricity and hydrogen leading to proportionately larger reductions in fossil fuel use (shown in Chapter 1, Figure 1.13). Combining the BLUE Map and BLUE Shifts scenarios leads to both the BLUE Shifts scenario's lower fuel use and the BLUE Map scenario's changes in fuel shares. The BLUE Map and BLUE EV scenarios achieve a two-thirds reduction in petroleum fuel use in 2050 compared to the Baseline in that year, with the main difference being that electricity's share is much higher in the BLUE EV scenario. Combining either of these scenarios with the BLUE Shifts scenario results in even lower overall fuel use, with a similar fuel mix.

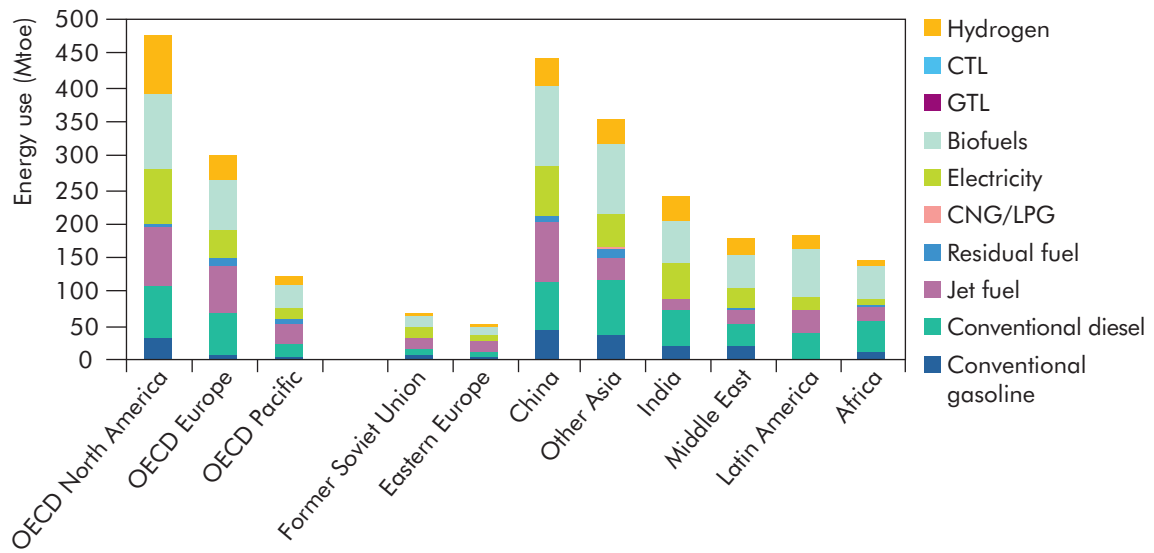
Figures 2.3 to 2.5 show the projected regional consumption of different fuels in 2050 in the Baseline, BLUE Map and BLUE EV scenarios. Two features are common to all these scenarios. First, transport fuel use grows more in China, Other Asia and India than in any other region or country. This reflects expected rates of growth in the population and wealth of these regions relative to other regions. Second, although total fuel demand and the mix of that demand varies between scenarios, within each scenario the pattern of demand is quite similar for all regions. This is consistent with the global nature of transport fuel markets, which generally aligns prices and so incentivises similar patterns of vehicle and fuel use.

Figure 2.3 ▶ Fuel type by region, Baseline scenario, 2050

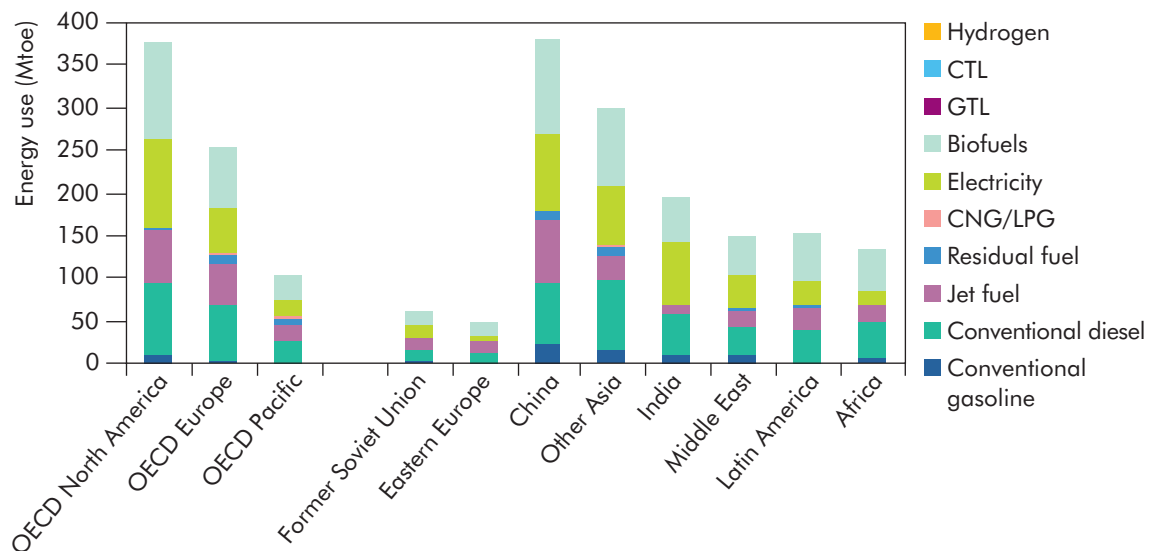


Key point

The role of Asian countries will grow in total oil imports for the transportation sector by 2050.

Figure 2.4 ▶ Fuel type by region, BLUE Map scenario, 2050**Key point**

In the BLUE Map scenario, low-GHG fuels substitute fossil fuels to drastically reduce GHG emissions.

Figure 2.5 ▶ Fuel type by region, BLUE EV scenario, 2050**Key point**

In the BLUE EV scenario, electricity takes over hydrogen if fuel cells vehicles do not reach mass market.

The BLUE Map scenario envisages most conventional gasoline and diesel vehicles being replaced by large numbers of hydrogen, FCVs and EVs by 2050 (Figure 2.4). Massive levels of investment would be needed in refuelling infrastructure for either of these technologies – let alone both of them – to play a major role. Although it is unlikely, the BLUE Map scenario assumes that they both play a partial role in all regions rather than forcing a choice between them in different regions.

By contrast, in the BLUE EV scenario, EVs are assumed to dominate in all regions by 2050. This scenario has been further developed for the current analysis (Figure 2.5). In *ETP 2008*, a similar scenario was created for FCVs. That scenario is not included here as no major additional analysis of the FCV option has been undertaken.

Electricity scenarios

The BLUE Map scenario projects that, from around 2015, EVs and PHEVs are sold in increasing numbers. EV and PHEV sales are each projected to reach about 50 million around the world by 2050, with combined stocks of over 1 billion such vehicles on the road in that year. In the BLUE EV scenario, the stock of EVs and PHEVs is even greater.

The electricity to run these vehicles must, of course, be generated and is additional to the electricity generated for other purposes. In the BLUE Map scenario, about 8% of all electricity generation in 2050 is projected to be used to power electric vehicles, and in the BLUE EV scenario, about 17%.

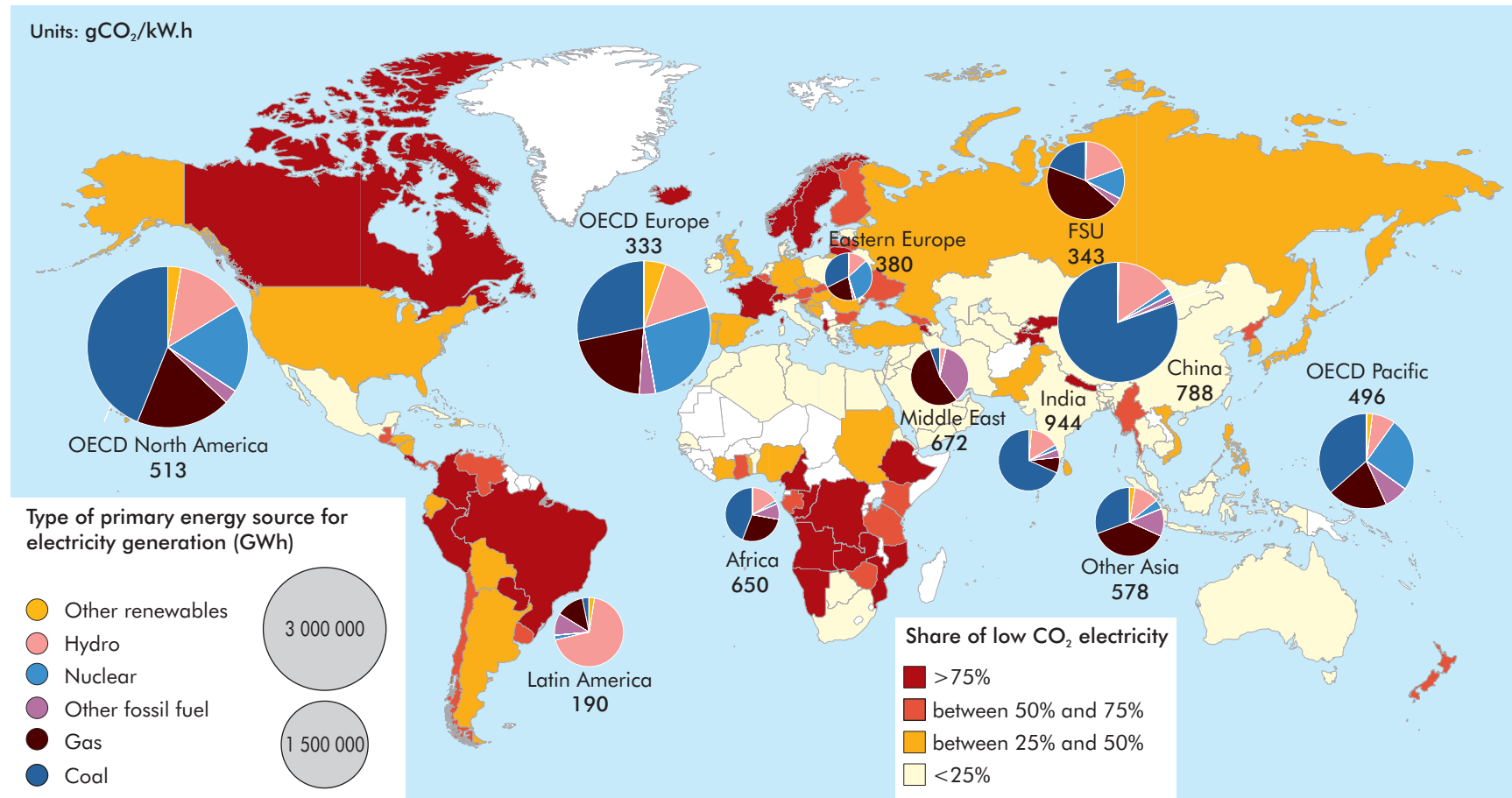
Figure 2.6 shows by region the approximate level of CO₂ emissions produced for each kWh of electricity generated in 2006. The data are broad averages that mask significant country-by-country variations in some regions. Electricity generation also varies widely within regions according to the time of year and time of day. As shown in the figure, average emissions varied from a low of 190g CO₂/kWh in Latin America to a high of 944g CO₂/kWh in India. Worldwide, electricity generation in 2006 emitted on average 504g CO₂/kWh produced.

Figure 2.7 shows the worldwide electricity generation mix in the Baseline and BLUE Map scenarios, excluding any additional electricity generation needed for EVs and PHEVs.¹ In the Baseline scenario, most of the 50 petaWatt-hours (PWh) generated in 2050 come from fossil fuels, with low GHG generation from renewables and nuclear power constituting just over 20% of the total. In the BLUE Map scenario, strong efficiency improvements in electricity-using equipment around the world result in a reduction in demand. An increasing proportion of electricity generated comes from low CO₂ sources, including renewables, nuclear power and fossil fuel generation fitted with carbon capture and storage (CCS), reaching 60% of generation in 2030 and nearly 100% in 2050.

The CO₂ emissions attributable to EVs and PHEVs are dependent on the generation mix of the electricity that fuels them. The CO₂ impact of the introduction of EVs and PHEVs therefore depends on developments in the electricity generation mix and on the rate at which EVs and PHEVs are introduced in different regions. Reductions

1. Very few EVs and PHEVs exist in the Baseline scenario.

Figure 2.6 ▶ Electricity generation by energy source, 2006

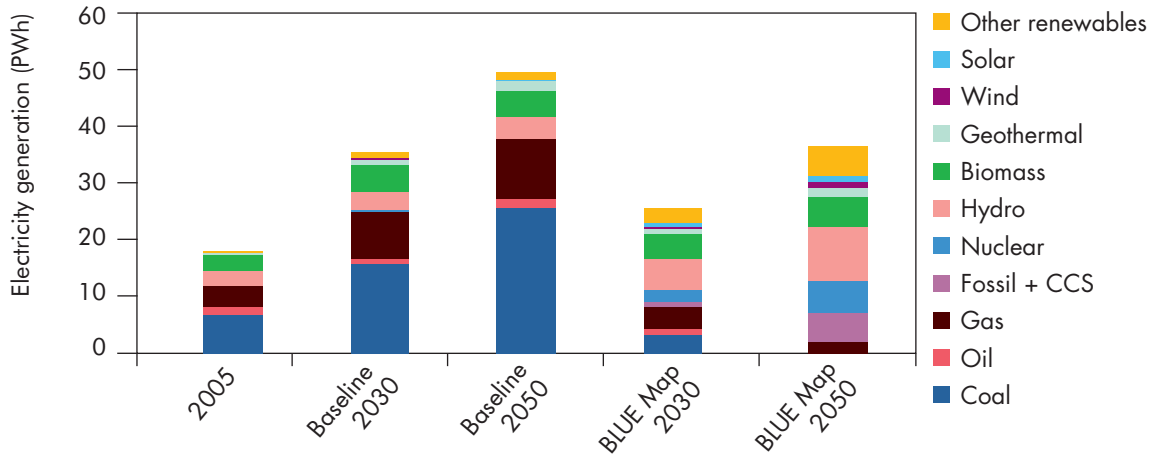


The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Key point

Few countries have more than half of electricity generated from low-GHG sources, showing electricity grids are not currently ready for low-GHG electric vehicles.

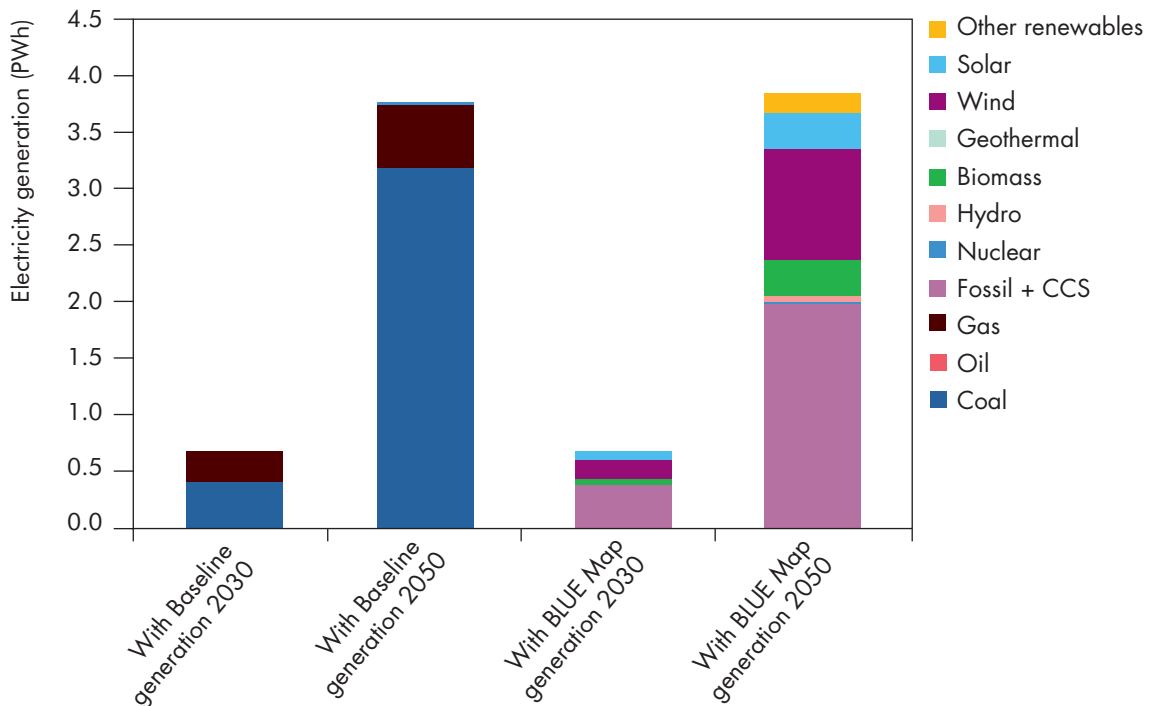
Figure 2.7 ▶ Total worldwide electricity generation by fuel, Baseline and BLUE Map



Key point

De-carbonising the electricity sector requires a revolution in how energy is used.

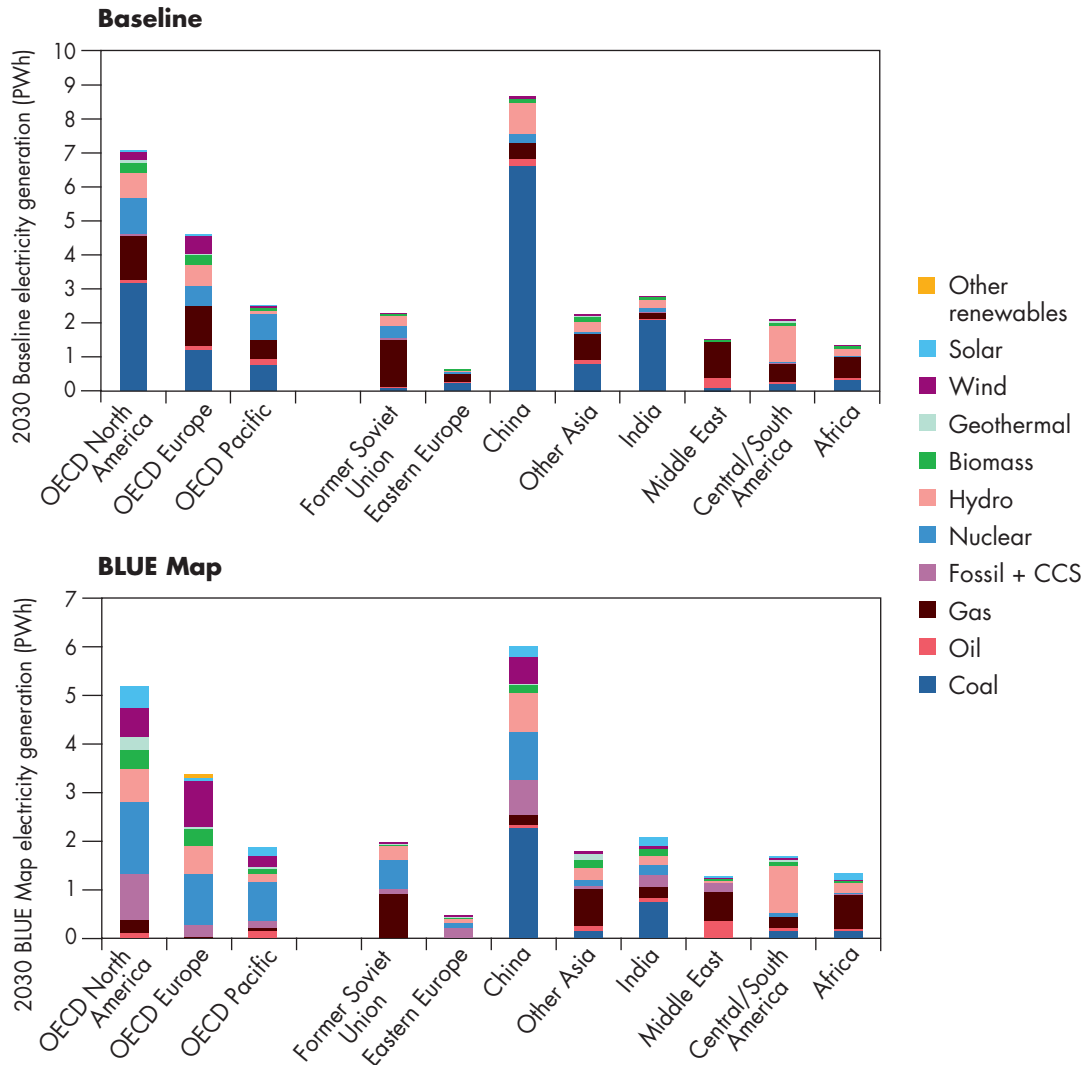
Figure 2.8 ▶ Sources of the additional worldwide electricity generation needed for the number of EVs projected in the BLUE Map scenario



Key point

Growth in use of EVs will require parallel greater development of electricity grids.

Figure 2.9 ▶ **Baseline and BLUE Map electricity generation in 2030 by region and fuel type**



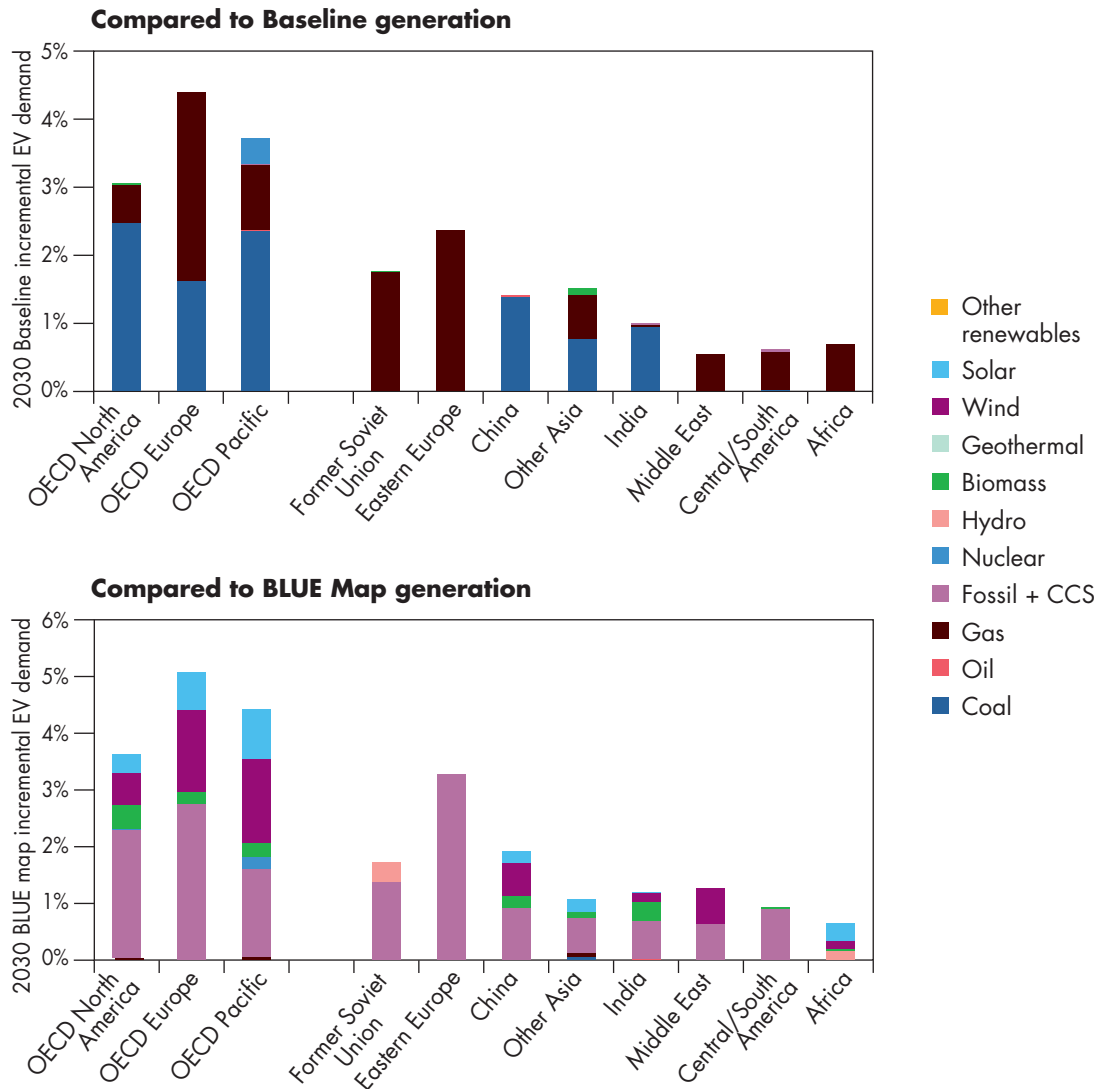
Key point

The BLUE Map scenario shifts generation to lower GHG intensive forms in all regions, compared to the Baseline scenario.

in CO₂ emissions are far greater with the electricity mix implicit in the BLUE Map scenario than with that implicit in the Baseline scenario. Reductions also increase in the BLUE Map scenario as time goes on and as generation becomes progressively less carbon intensive around the world.

The number of EVs and PHEVs in 2050 in the BLUE Map scenario would create demand for an additional 3.5 PWh of electricity. Figure 2.8 shows the most likely source of the additional power needed, showing the electricity generation mix both in the Baseline scenario and in the BLUE Map scenario. With the BLUE Map scenario for EVs but with Baseline electricity generation, this additional demand would be met almost entirely from coal-fired power plants. With the BLUE Map

Figure 2.10 ▶ Additional generation needed for the number of EVs projected in the BLUE Map scenario, 2030



Key point

The additional electric vehicles in the BLUE Map scenario would require 2.5% to 4% more electricity in OECD regions and 0.5% to 2% in non-OECD regions, primarily from coal and gas, if the EVs occurred in a Baseline scenario with respect to the electricity generation mix. In the BLUE Map scenario, the electricity for these EVs is supplied by less intensive GHG electricity.

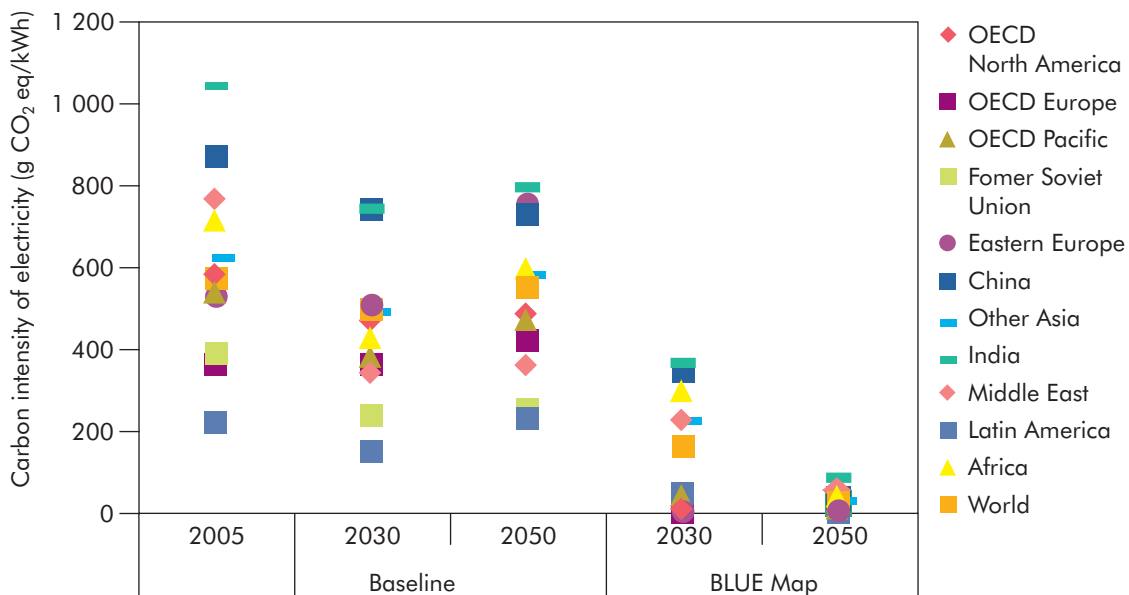
electricity scenario, given the policies to promote low-GHG generation, additional electricity demand would be met from a mix of sources, with large portions from fossil fuel power stations fitted with CCS and from wind power.

Figure 2.9 shows the regional generation mix in the Baseline and BLUE Map scenarios. Figure 2.10 shows the incremental electricity demand required for EVs in the BLUE Map scenario in 2030 considering the additional generation mix of the Baseline and the BLUE Map scenarios. This shows that in the Baseline scenario,

where there is no shift to lower-GHG forms of electricity generation, an increase in EVs and PHEVs in China and India could result in significant additional GHG emissions from the electricity sector. If electricity generation has shifted to almost all low-GHG sources, as in the BLUE Map scenario, there would be advantage in all regions increasing the uptake of EV and PHEVs by 2030.

Projections of the GHG intensity of electricity generation in different regions are shown in Figure 2.11. In the Baseline scenario, generation from low-GHG sources increases steadily but after 2030 is more than offset by the increase in fossil fuel generation, especially from coal. The net effect is a reduction in GHG intensity until 2030 but a slight increase from 2030 to 2050. In the BLUE Map scenario, global electricity generation is progressively decarbonised. The world average carbon intensity drops from 550 g CO₂/kWh in 2005 to about 160 g CO₂/kWh by 2030, and falls close to zero in 2050. In 2030, the CO₂ intensity of generation in regions such as China and India is much higher than the average, but by 2050 all countries and regions are below 100 g CO₂/kWh.

Figure 2.11 ► GHG intensity of electricity generation by region and scenario

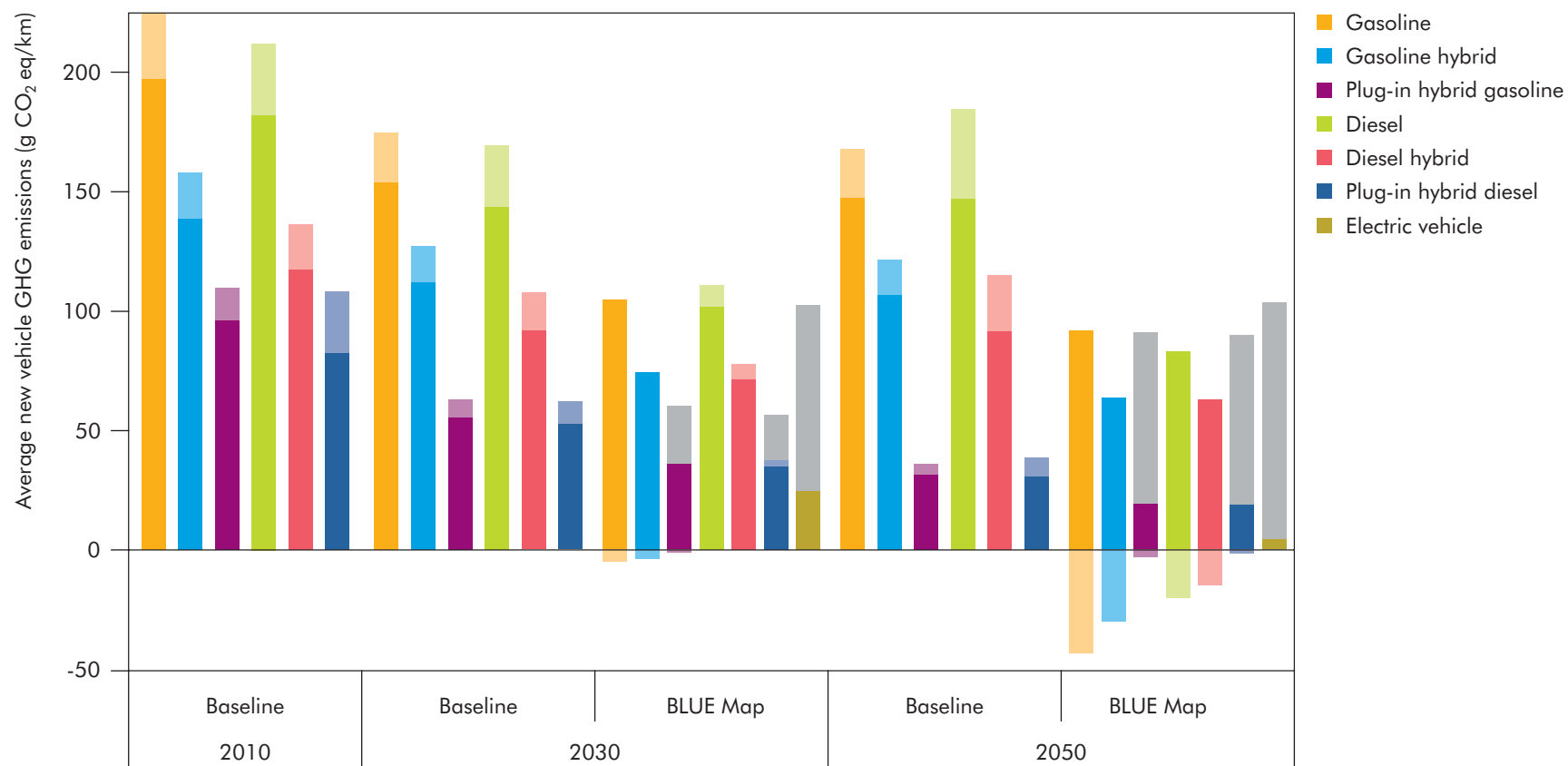


Key point

By 2050, worldwide electricity is almost GHG-free in the BLUE Map scenario.

The impact of the EV and PHEV electricity demand on GHG emissions in the different scenarios, taking account of regional GHG intensities of electricity generation, is shown in Figure 2.12. The GHG emissions of EVs are not always lower than those of their liquid fuel counterparts if the electricity that fuels them comes from GHG intensive electricity generation. Figure 2.12 shows EV and PHEV GHG emissions for the electricity generation mixes in both the Baseline and BLUE Map scenarios. The GHG emission reductions attributable to EVs are far higher with the decarbonised generation in the BLUE Map scenario. But ICE vehicles also emit much less GHG in the BLUE Map scenario, especially by 2050, due both to efficiency gains and to the use of low-GHG biofuels.

Figure 2.12 ▶ New vehicle well-to-wheel CO₂ emissions per km by scenario and fuel type



Note: The darker part of each bar shows the vehicle CO₂ emissions; the lighter section shows the well-to-tank emissions, during fuel production and transport. For EVs and PHEVs, the grey part in BLUE Map shows the CO₂ from electricity generation that would occur with a Baseline rather than BLUE Map generation mix. The characteristics of the vehicles considered here correspond to those described in chapter 3.

Key point

CO₂ intensity improves for all modes thanks mainly to vehicle efficiency, advanced biofuels, and the use of low-carbon electricity and hydrogen.

If a low-GHG transport system is to be achieved, reducing the carbon intensity of electricity generation is as important as developing the infrastructure to enable EVs to be recharged. In addition, as conventional vehicles become much more efficient over time in the BLUE Map scenario, the CO₂ advantage of EVs in many regions will decline over time unless electricity generation decarbonises at the rates envisaged in the BLUE Map scenario. But, if electricity generation does decarbonise at those rates, EVs offer superior CO₂ outcomes to other LDVs in every region by 2030, ranging from zero to 80 g CO₂ eq/km for EVs compared to 65 g CO₂ eq/km to 130 g CO₂ eq/km for non-EVs. By 2050, EVs average 20 g CO₂ eq/km or less across all regions, with non-EVs reaching 40 g CO₂ eq/km to 80 g CO₂ eq/km.

Transport fuels and fuel production technologies

Petroleum fuels offer a number of benefits which make it likely that they will continue to dominate the overall fuel mix. These same factors also mean that it will probably take substantial, long-term policy pressure to achieve a switch to large amounts of alternative fuels. The benefits of petroleum fuels include:

- High energy density.
- Strong demand from the current stock of vehicles and a widely established infrastructure for delivery to users.
- Relatively low cost. Even at USD 100/bbl of oil, the production of most refined petroleum fuels is likely to cost less than USD 0.70/L.
- Easy, low-cost handling and transport.
- Extensive experience and knowledge of fuel systems, coupled with considerable progress having been made in optimising them. For other fuels, much learning and optimisation is still needed and will take decades.
- Ease of long-term storage.

But petroleum fuels also have at least two major drawbacks: potential supply limitations, including for many countries significant geopolitical dependencies, and high CO₂ emissions. For both of these reasons, there are strong incentives to develop and secure acceptable substitutes. Air pollution is another important concern, though this can be controlled through improved petroleum fuel quality and through technology, e.g. through catalytic conversion. OECD countries are on track to reach very low levels of most pollutant emissions and this should also be possible in non-OECD countries if necessary investments are made at refineries (e.g. for sulphur removal) and in vehicles (e.g. for post treatment devices).

The IEA World Energy Outlook 2008, WEO 2008 (IEA, 2008b) reviewed potential supply limitations, including the evidence of decline rates in existing oil fields. It concluded that ensuring adequate supplies of oil over the next two decades will be challenging and require enormous investments. This will increase the price of fossil fuels, which should in turn help to make other fuels more competitive. High prices should also encourage improvements in fuel efficiency. But oil prices

alone, unless they are very high, are unlikely to be sufficient to produce the very significant shift away from fossil fuels that is needed to reduce CO₂ emissions.

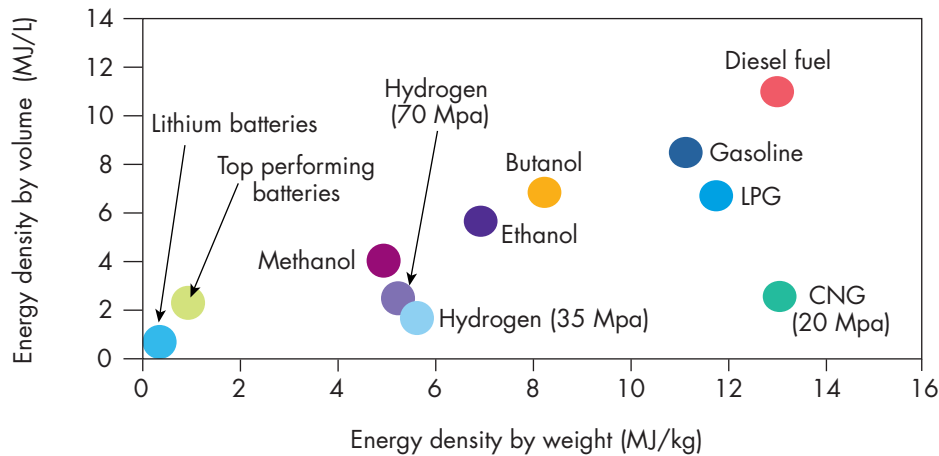
CO₂ is one of the main products of fuel combustion. The GHG impacts of transport depend on two important factors: the efficiency of the propulsion system and the way in which it is operated; and the type of fuel used and the way in which it is produced and distributed. A range of feedstocks and fuels, summarised in Table 2.1, is reviewed in this chapter in terms of GHG emissions and costs.

Table 2.1 ► Fuels and their production process

Fuel	Feedstock	Process/Notes
Liquid petroleum fuels: gasoline, diesel, kerosene, jet fuel	Oil from both conventional sources and non-conventional sources such as heavy crudes and tar sands	Refining
Liquid synthetic fuels	Natural gas, coal	Gasification/FT (with or without CCS)
Biodiesel	Oil-seed crops	Esterification, hydrogenation
Ethanol	Grain crops	Saccharification and distillation
Ethanol	Sugar crops (cane)	Distillation
Advanced biodiesel (and other distillate fuels)	Biomass from crops or waste products	Gasification/FT (with or without CCS)
Compressed natural gas	Natural gas	Gasification/FT (with or without CCS)
Electricity	Coal, gas, oil, nuclear, renewables	Different mixes in different regions (with or without CCS)
Hydrogen (H ₂)	Natural gas	Reforming, compression; centralised (with or without CCS), or at point of use
	Electricity	Electrolysis at point of use
	Direct production using e.g. wind, solar, nuclear energy	High-temperature process

Notes: FT = Fischer-Tropsch synthesis. CCS = carbon capture and storage.

Figure 2.13 shows the energy density of different fuels by weight and by volume. The position of battery technologies in this figure highlights the fact that, given the limited physical capacity of most vehicles, EVs suffer from being able to travel only limited ranges before they need refuelling.

Figure 2.13 ▶ Energy density of batteries and liquid fuels

Sources: Various, including IEA data on the relationship between volumetric and mass density of batteries and IEA assumptions on the efficiencies of engines (25% to 30% for internal combustion engines), fuel cell systems (75%) and electric motors (90% to 95%).

Key point

Liquid fuels supremacy is likely to continue, especially for the long-distance modes of transportation.

Liquid fuels from conventional and unconventional oil feedstocks

The vast majority of transport fuels today derive from the refining of crude petroleum oil. This is a well-established technology, although the demand for ever cleaner fuels (such as those with reduced sulphur levels) and changes in the fuel mix (for example to meet increasing demand for diesel fuel in Europe) present investment challenges. The mix of extracted crude oils is also evolving, with average crudes becoming heavier in recent years. These trends are expected to continue and will drive new investments in the future, probably slowly increasing the average cost of refining.

Alternative, unconventional sources of petroleum-based hydrocarbons are being developed around the world. These could significantly extend supplies, almost certainly at higher cost than conventional supplies and, in some cases, with higher CO₂ emissions from extraction and processing. In the Baseline scenario, these fuels play an increasingly important role after 2030 and significantly increase CO₂ emissions from the transport sector in 2050. They include:

- **Heavy oil and extra-heavy oil** are both dense and viscous oils containing large molecules that incorporate significant amounts of sulphur and metals. The United States Geological Survey (USGS) estimates that the resources of heavy oils are particularly concentrated in the Orinoco heavy oil belt (Venezuela), expected to contain 90% of the world's extra-heavy oil and roughly 50% of the global technically recoverable heavy oil resources (226 Gbbl out of 434 Gbbl).

- **Oil sands** are a mixture of sand, water and bitumen, from which bitumen must be extracted for further use. Oil sands are primarily concentrated in Canada. According to the USGS, Canada's estimated technically recoverable resources of bitumen constitute about 80% of the worldwide resources and amount to 530.9 Gbbl in 2003. The *BP Statistical Review of World Energy* (2009) reported that the proved reserves of Canadian oil sands amounted to 150.7 Gbbl in 2008. According to the Government of Alberta, the remaining established reserves are 170.4 Gbbl and the ultimate potential (recoverable) is 315 Gbbl (Burrowes *et al.*, 2009).
- **Oil shale** is a "fine-grained sedimentary rock containing organic matter that yields substantial amounts of oil and combustible gas upon destructive distillation" (USGS, 2005). This organic matter is often referred to as kerogen, an immature form of oil that has never been exposed to high temperatures. When the rock is heated to between 350°C and 400°C, it yields 20 to 200 L of shale oil per tonne of shale. The most complete estimates of oil shale availability have been published by the USGS, which illustrate that deposits of oil shale are in many parts of the world. The bulk of the world's oil shale resources are located in the United States, where there are estimated to be more than 2 000 Gbbl of oil shale of medium quality (about 75% of the world total), capable of yielding more than 40 L of fuel per tonne of shale. Given the high cost of production, the viability of a large-scale, oil-shale industry is not foreseen in the near term. Today, few if any deposits can be economically mined and processed for shale oil in competition with petroleum. In large-scale production, oil-shale processing would be expected to generate about five times the CO₂ emissions produced by conventional oil refining. Precise estimates, however, need to be calibrated to the shale oil yields and characteristics.

Production from heavy oils and bitumen can take place in various ways. Some heavy oils can be extracted with conventional methods in use for lighter oils or may require thermal methods of recovery. Bitumen from the oil sands can be extracted in two ways, mining and *in situ* extraction. For oil sands less than 75 m below the Earth, ore dug up from the open-pit mine is mixed with water and pumped to a facility where the material is mixed with warmer water to recover the bitumen from the sand. Currently, mined bitumen represents over half of oil sands production. However, 80% of the oil sands resource is too deep to mine. In these cases, some form of *in situ* recovery is required to produce bitumen. *In situ* oil sands production uses steam to separate the bitumen from the sand under the Earth after which it is recovered through wells. The dominant technology for *in situ* production is steam-assisted gravity drainage (SAGD); however, new technologies are emerging that use solvents or *in situ* combustion in place of steam.

Once extracted, oil sands bitumen is either diluted with lighter petroleum products in order to meet pipeline specifications and is sent to refineries, or it is transformed into an upgraded crude oil comparable to a high quality, light, sweet crude oil. The upgrading process is similar to a refining process and upgraded bitumen is known as synthetic crude oil (SCO). Since bitumen is hydrogen deficient, it is upgraded through both carbon removal (coking, which yields petroleum coke, typically burned for energy recovery) and hydrogen addition (hydrocracking). The energy efficiency of the process as a whole is about 75%.

The process has been estimated to emit between 22 kg and 34 kg of CO₂/GJ syncrude, more than double the 10 kg CO₂/GJ for conventional oil refining. Some recent life-cycle emission estimates, however, indicate well-to-wheel GHG emissions for oil sands extracted with the SAGD process that are about 10% to 15% above those of the average crude oil processed in the United States. Recent unpublished studies commissioned by the Alberta Energy Research Institute have also shown that life-cycle GHG emissions from oil sands bitumen can overlap with those considered as conventional crudes being used in the United States (such as heavy crudes and Nigerian crude, including flaring emissions).

In total, current production from oil sands represents about 1 300 bbl/day. This could be expanded at perhaps 10% per year, reaching 4 million to 6 million bbl/day by 2030. The latest forecast from the Canadian Association of Petroleum Producers indicates that oil sands production (including bitumen and SCO) may increase to 3.3 million bbl/day by 2025. This expansion could be halted if competition from much lower CO₂ alternative fuels becomes economically competitive. Other factors that impact the rate of growth of bitumen production from oil sands include variations in the price of oil, and the effects of the costs of meeting existing and upcoming environmental regulations such as GHG emission standards.

Synthetic liquid fuels

Liquid fuels with properties similar to petroleum products can be produced from the gasification (*i.e.* the generation of syngas, a mixture of hydrogen and carbon monoxide) and Fischer Tropsch (FT) synthesis (*i.e.* the conversion of syngas into liquid fuels) of any hydrocarbon feedstock, including natural gas. Coal and biomass are also suitable feedstocks, provided that water is used in the gasification process to supply hydrogen. These synthetic fuels are commonly referred to by their acronyms GTL, CTL and BTL, respectively.

The predominant commercial technologies for syngas production in GTL plants are steam methane reforming and partial oxidation. In the first case, methane and steam are catalytically and endothermically converted to hydrogen and carbon monoxide. In the second case, syngas is obtained from the exothermic, non-catalytic reaction of methane and oxygen. The two approaches produce syngas with appreciably different compositions, either above or below the hydrogen-to-carbon-monoxide ratio required by the FT synthesis of liquid fuels. This is why steam methane reforming and partial oxidation can be combined in the autothermal reforming process, which allows using the heat generated in the partial oxidation approach to be fed in to the steam reforming. Advanced technologies, currently at a demonstration stage, also use CO₂ gas as raw material, eliminating the need for oxygen supply for the syngas reaction.

In the case of coal and biomass feedstocks, two approaches are possible: direct and indirect liquefaction. In the case of indirect coal liquefaction (also suitable for BTL), the feedstock is broken down into hydrogen and CO₂ by gasification with steam. The FT process follows the gasification step and involves the reaction of the syngas over a catalyst at relatively low pressure

and temperature. It yields different products, depending on the catalyst used and the temperature reached in the reactor. High-temperature FT synthesis (operating at 300°C to 350°C and 20 to 30 bar) leads to the production of synthetic gasoline and chemicals. Low-temperature FT synthesis leads to the production of waxy products that can be cracked to produce synthetic naphtha, kerosene or diesel fuel. The diesel produced in synthesis plants is a high quality product with an energy density similar to conventional petroleum diesel, a high cetane number and low sulphur content (sulphur compounds present in the feedstock need to be removed to prevent poisoning of the catalysts). Very high quality aviation kerosene (jet fuel) can also be produced. The conversion efficiency of the process is typically about 55%. By using other reactors and units other than a FT reactor in the second step, a range of other products can be derived from syngas, including methanol and dimethyl ether (DME).

The technology is well established, although there is still room for improvement in conversion efficiencies. One of the biggest technical challenges is optimising heat recovery transfers between the syngas generation and the subsequent syngas conversion phases. The thermal efficiency of synthesis plants can also be increased by making better use of the heat generated in the exothermic FT processes, for example through the co-production of steam or electricity.

In the case of direct coal liquefaction, hydrogen needs to be added to the organic structure of coal, breaking it down to the point at which distillable liquids are produced. The basic process involves dissolving coal in a solvent at high temperature and pressure, followed by the addition of hydrogen over a catalyst. Liquid yields can exceed 70% of the dry weight of the feedstock, and thermal efficiencies can approach 70%. The products of direct liquefaction, however, need further upgrading to be used as transport fuels.

Although synthesis fuels are high quality, direct substitutes for petroleum fuels, few GTL or CTL facilities are currently in operation (GTL in Qatar and Malaysia; CTL in South Africa). Others are being built or planned, notably in Nigeria (GTL), in China and India (CTL).

High costs, long construction times and completion delays have deterred investment in new facilities. Optimally sized plants are very large and can take as long as ten years to be brought on stream. GTL is likely to be most cost effective where it can be undertaken near to stranded natural gas reserves. Total reserves of stranded gas are estimated to amount to around 140 000 Mtoe, around half of all global gas reserves and equivalent to 60 years of current gas use. Around half of these reserves are situated in the Middle East, with other significant shares in Russia and the Central Asian republics. But as the cost of shipping liquefied natural gas (LNG) declines, there are fewer areas where GTL is the best option for bringing stranded gas reserves to the market.

Future GTL and CTL production capacity is expected to grow only slowly given the huge and risky investments required. However, after 2030 growth may accelerate as opportunities to expand the supply of conventional and even unconventional oil begin to decline. In the Baseline scenario, it is assumed that GTL and CTL fuels constitute about 5% of transport fuel use in 2050, rising to 10% in the High Baseline scenario. Since these are high-CO₂ fuels, the growth

in their use also causes the average GHG intensity of transport fuels in these scenarios to grow over time.

Methanol and dimethyl ether

Methanol is a high-octane alcohol that has been used as a fuel in some types of vehicles, including racing cars. Its high toxicity and relatively low energy density have severely limited its use in commercial applications. But methanol could also be used as a fuel for FCVs, since it is a simple and potentially very pure compound that stores hydrogen. The reforming of hydrogen from methanol on board vehicles is a possible solution to the energy storage problems of FCVs.

Methanol can also be converted into DME, a fuel physically similar to LPG. DME can be stored in low-pressure tanks as a refrigerated liquid at -25°C , or in pressurised tanks. DME is non-toxic and can be used in diesel engines, with excellent combustion properties and good energy density. In experimental tests, DME combustion produces very little nitrous oxides or particulate matter. Current global production of DME is less than 0.5 Mt per year, for use mainly as an aerosol propellant.

Various process designs have been proposed for co-producing methanol and DME, and for the cogeneration of DME and electricity. Such designs circumvent the problem of the incomplete conversion of feedstock into DME and could lower production costs. There have also been recent developments in the direct production of DME from synthesis gas, and in the coal-based DME production capacity China has been registering impressive increases in recent years. A rapid expansion of Chinese DME production is planned, to more than 4 Mt per year in 2009. Further gas-based projects have recently been inaugurated or are planned in Australia, Iran and Japan.

The most significant barrier to the wider use of DME as a transport fuel is the absence of a distribution infrastructure. In addition, to compete with conventional diesel, DME needs to be produced on a large scale, which requires heavy capital investment. The development of commercial vehicles that could run on either diesel or DME, or on mixed diesel and DME, would also help DME to penetrate the market. Given the barriers to their uptake, neither methanol nor DME are included in the subsequent analysis of fuels in this chapter.

Ethanol

Ethanol is an alcohol that is liquid at ambient temperature and pressure. It can be used in blends with gasoline in existing vehicles. Ethanol is a clean, high-octane fuel although its energy density is only about 65% that of gasoline. Its use as a blend tends to lower nitrogen oxide (NO_x) emissions but to raise the evaporative emissions of hydrocarbons, including toxic compounds such as aldehydes.

Ethanol has so far been introduced into the fuel market for gasoline engines primarily in low-percentage blends, such as 10% ethanol and 90% gasoline. In some countries, such as Sweden and in parts of the United States, higher level

blends of up to 85% ethanol are available. In Brazil, most vehicles are capable of running on any blend of ethanol and gasoline. Both are available separately at most fuel stations, with most gasoline being sold already blended with an ethanol content of 20% or 25%.

Although ethanol can be produced from fossil fuels such as natural gas, nearly all ethanol production today is from bio-feedstocks, typically either from grains or from sugar crops such as cane. The IEA (2004) reviewed in detail the types and characteristics of different methods of ethanol production. Conventionally, sugars are fermented or starch is converted into sugar, which is then fermented into ethanol. The ethanol is then distilled to fuel grade. In OECD countries, most ethanol fuel is produced from starchy crops such as maize, wheat and barley, but ethanol can also derive from potatoes, sorghum and cassava. The world's largest ethanol producer is the United States, primarily from maize. The second-largest producer is Brazil, where ethanol derives entirely from sugar cane.

Advanced (second-generation) ethanol

In conventional processes, only the starchy or sugary part of the plant is used for the production of fuel. These starchy parts represent a fairly small percentage of the total plant mass, leaving large quantities of fibrous remains such as seed husks and stalks. Much current research is focused on innovative processes to use these materials, which are made up of 20% to 45% by weight of cellulose, to create fermentable sugars. This could lead to significant improvements in production efficiencies and allow greater use to be made of non-food crops that can be grown in locations that do not compete with food production.

The production of ethanol from cellulose would create opportunities to produce fuel from a wider range of potential feedstocks, including waste materials and crops such as grasses and trees. Fast growing crops that are rich in cellulose, such as poplar trees and switchgrass, would be well suited to produce ethanol. In North America, much attention is being given to maize stalks and other grain straws. In Europe, attention is focused on food-processing waste, grass and wood crops. In Brazil, sugar cane stalks (bagasse) are already used to provide process energy for ethanol conversion once the sugar is removed, but the cellulosic material is not itself converted into ethanol. Much of the sugar cane crop is still left in the field and burned. Advanced conversion processes would allow the full use of the biomass available in the sugar cane plant.

The production of ethanol from woody and fibrous feedstocks remains technologically challenging because all the steps of the production process need to be optimised. These issues are covered in detail in IEA (2008c). Other research is directed towards the possibility of producing all the required enzymes inside the reactor vessel, thereby enabling the microbial production both of the enzymes that break cellulose down into sugars and of those that ferment the sugars to ethanol. This consolidated bioprocessing is seen by many as the logical end point in the evolution of biomass conversion technology.

Although a good deal of progress has been made at a research level in recent years, no commercial scale conversion facilities have yet been built. System optimisation and cost reductions are needed if large-scale plant construction is to

be justified. The United States, in particular, is providing substantial RD&D funding to tackle these issues, and is funding small and intermediate scale test facilities. At present, it is not possible to judge when and how the first large-scale ligno-cellulosic plant is likely to be built.

Biodiesel

2

Biodiesel is a fuel that can replace or complement petroleum diesel fuel. It typically derives from converting vegetable oils to methyl ester, often called fatty acid methyl ester (FAME). Feedstocks commonly include oilseed crops such as soy, sunflower or rapeseed, and other crops such as palm and coconut. It can also be produced from used frying oil or from animal fats such as beef tallow, poultry fat or pork lard.

The drawbacks of biodiesel are that it is incompatible with some elastomers and rubber, although this has been resolved in recent vehicles. It also tends to gel at low temperatures, although this can be mitigated by mixing it with petroleum diesel. In addition, it is miscible with water, which can reduce its heat of combustion and accelerate the corrosion of fuel system components.

Conventional biodiesel production technologies

Most biodiesel is produced through the transesterification of vegetable oil, frying oil or animal fats. In this process, cleaned up oils and fats are mixed with an alcohol (usually methanol) and a catalyst (usually sodium hydroxide or potassium hydroxide) causing the oil molecules to break apart and reform into esters and glycerol. These are then separated from each other and purified. The resulting esters are the biodiesel product.

FAME biodiesel produced this way is highly suitable for use in standard diesel engines. It can be used in its pure form or blended with conventional diesel fuels. FAME biodiesel is sulphur free. Pure FAME biodiesel also acts as a mild solvent that can help keep engines clean and well running. Biodiesel blends also improve lubricity: even a 1% blend can improve lubricity by up to 30%, helping engine components last longer. Biodiesel contains only about 90% as much energy as diesel fuel, but its high cetane number and lubricity typically lead to efficiencies just a few percentage points below that of petroleum diesel.

The production of biofuels from vegetable oil is, however, subject to a number of practical and operational constraints. Oil-seed crops other than tropical palm oil yield fairly small amounts of fuel per hectare of crop production. Growing crops for biofuels can also impact negatively on the production of food supplies. Crop-based biofuels can also be expensive, depending on the price of the feedstock crops.

Advanced production technologies for biodiesel

A number of other approaches to producing biodiesel-like fuels are already commercial or under development. These are summarised here, and are documented in more detail in IEA 2008c.

High quality, diesel-compatible fuel and even jet fuel can be produced by hydrocracking vegetable oil and animal fats. This technology is fully commercial. Hydrocracked biojet fuel has been tested in aircraft and found to be more suitable than FAME biodiesel as it has a much lower freezing point. The most cost-effective approach to the production of this biodiesel may be to integrate the process into oil refineries, where hydrocracking facilities and the necessary quality control mechanisms are already in place. Although hydrocracking may help to make higher quality biofuels from oil-crop feedstocks, it does not remove the basic drawbacks associated with those feedstocks, such as low yields, competition with food, and potentially high feedstock prices.

It is also possible to convert biomass into liquid or gaseous biofuels. One approach is to use a process similar to that used for CTL and GTL fuels, *i.e.* gasification combined with FT synthesis. In this method, biomass must first be converted into a syngas through a two-step process involving:

- Thermal degradation of the biomass, which converts it into the syngas components hydrogen and CO, typically also producing methane, longer hydrocarbons and tars.
- Cleaning of the derived gas. Tar cleaning is particularly difficult but is essential to obtain a syngas that can meet the FT feed-gas specifications and avoid damaging catalysts.

Then, as with other synthetic fuels, FT synthesis is used to convert the syngas into BTL fuels. The products, such as naphtha or diesel, are of a similarly high quality as those from other fuel synthesis processes.

The BTL approach has a particular advantage in that it allows non-food biomass feedstocks, such as potentially low-cost perennial grasses or short rotation coppice, to be used to produce biofuel. Agricultural waste products, such as rice husks, could also be used. But it is important for the design of cost-effective BTL plants that feedstocks are sufficiently heterogeneous to avoid the need for excessive pre-processing and production purification processes.

Diesel fuel can also be produced through the hydrothermal upgrading (HTU) of biomass. In this method, cellulosic materials are first dissolved in water under high pressure and at relatively low temperatures. This converts them into a biocrude liquid. This biocrude can then be upgraded to diesel fuel by heating and hydrogenation. A wide range of organic-rich feedstocks can be used, including municipal wastes. Biocrudes may be capable of being used directly in heavy-fuel oil engines such as those on ships. More research and development (R&D) is needed into this type of process, and this should be a priority area for delivering relatively low-cost biofuels for heavy-duty transport applications.

Another approach is fast pyrolysis, in which biomass is quickly heated to high temperatures in the absence of air and then cooled down to form a liquid bio-oil. This liquid can be used for the production of chemicals or further refined into products such as diesel fuel, but its treatment has proven to be difficult. The approach is also used to convert solid biomass residues, such as bagasse, into a fuel that is easier to burn for process heat during the production of ethanol. At present, however, fast pyrolysis requires too much energy and is too expensive to be viable at scale.

Biofuels can also be produced from algae (see Box 2.1).

Box 2.1 ▶ **Algae-derived biofuels**

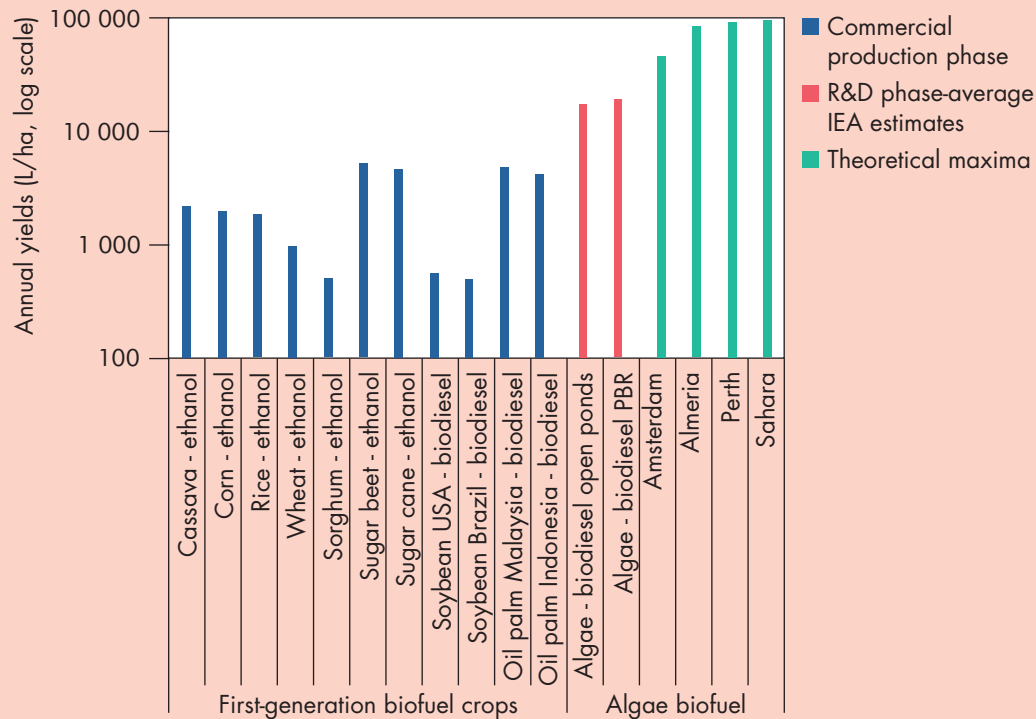
Algae are among the most efficient organisms on Earth at performing photosynthesis. They are particularly good at producing oils: their lipid content can reach 60% for some species (Christi, 2007) and they can double their mass in less than 24 hours. Algae are now being intensively researched and developed as a potential next-generation bioenergy and biofuel feedstock. In addition to their potential for high yields per unit land area, algae can grow in places unsuitable for agriculture, including industrial areas. Thus, their exploitation offers the potential prospect of a source of biofuel that avoids the damage to ecosystems and competition with agriculture associated with other bio sources.

Since the 1950s, algae have been cultivated in open ponds and used for food additives in a number of countries. More recently a new approach has been developed, using closed systems called photobioreactors (PBR). Both methods have advantages and disadvantages. Open ponds need less energy for operation but more nutrients and water than closed systems. PBR systems can provide better yields and are less subject to contamination by non-desired species, but they are currently more expensive per unit of oil produced.

About 60 biofuel testing and start-up companies are already in operation in 12 countries, about 70% of which are in the United States. These companies are approaching the process in a number of different ways. They typically release relatively little information, making it difficult to understand in detail the advantages and disadvantages of different approaches. Cost information is also scarce. As of mid-2009, none appeared to have reached a commercial scale of production.

The IEA has compared yield data from 14 projects using open pond systems and 23 using closed-system PBR technologies. These have also been compared to basic physical properties, where possible, as an additional check on possible limits. The average yields for both types of algae production approaches are well above those for agriculture-based biofuels (Figure 2.14). They are also well below maximum potential yields, indicating that yields may improve with further learning and optimisation. The averages may be better indicators of future commercial scale yields than the theoretical maxima that are based on optimal conditions that may only exist for short periods of time.

Figure 2.14 ▶ Comparison of annual yields for algae-derived and other biofuels



Sources: FAO, IEA, Cadoret et al.

Key point

Current prototype algae biofuel yields are higher than first generation biofuels and lower than the theoretical maximum yields for algae biofuels.

Hydrogen

Hydrogen (H_2) is a potential transport fuel both for ICEs hydrogen and for FCVs. Fuel cells use hydrogen as a fuel to generate electricity on board vehicles. The H_2 can also be produced on board the vehicle, for example from ethanol or other liquid fuels containing hydrogen. But increasingly it is expected that it will be more cost-effective to store hydrogen directly on board vehicles after producing it separately elsewhere.

Hydrogen can be produced from fossil fuels or from nuclear or renewable energy by a number of processes. These include water electrolysis, natural gas reforming, gasification of coal and biomass, water splitting by high-temperature heat, photo-electrolysis, and biological processes. Of the 8 EJ (about 190 Mtoe) of hydrogen currently produced each year, 40% is used in chemical processes, 40% in refineries and 20% in other areas. In 2003, 48% of all hydrogen was produced from natural

gas, 30% from oil and off-gases of refineries and chemical plants, 18% from coal, and 4% from electrolysis. Most of this hydrogen is produced on-site in refineries and chemical plants for non-energy uses.

Local scale production of hydrogen is currently based on water electrolysis and small natural gas reformers. Such production will be needed in the early phases of the introduction of hydrogen in transport, as the demand from only a limited number of vehicles will not support centralised production. Electrolysis is a costly process that produces high-purity hydrogen. The cost of electrolysis can be reduced significantly, but electricity remains an expensive input in most parts of the world. Small-scale natural gas reformers are commercially available. Several demonstration projects are testing units in industrial applications. In recent years, suppliers have considerably reduced the size of reformers, to 10x3x3 m, and increased their capacity, up to 500 to 700 normal m³/hour, equivalent to 5.5 GJ/hour to 7.5 GJ/hour.

When demand justifies centralised production, hydrogen can be produced at larger scale from natural gas or coal. Such processes will need to be combined with CCS if emission reduction is a goal. Large-scale natural gas based hydrogen production is an established process. Further RD&D could help lower costs, increase efficiency and enhance the flexibility of the process. Improved catalysts, adsorption materials, separation membranes and purification systems are also needed to produce hydrogen that is suitable for a wide range of uses.

Hydrogen production based on coal gasification and the water-gas shift reaction is also an established technology. It is more expensive than production from natural gas. Cheaper gasifiers and new oxygen production technologies may reduce the cost of hydrogen from coal in the future. The cogeneration of electricity and hydrogen from coal could also reduce costs.

Hydrogen can also be produced directly by algae. Genetic research is seeking ways to enhance algae's natural ability to produce hydrogen.

Finally, hydrogen can be produced through electrolysis from electricity generated by nuclear, wind, solar and other renewable sources. However, from an economic standpoint, the current electricity and hydrogen markets do not support these primary energy inputs to be used for hydrogen production.

Infrastructure will also be needed to distribute, store and deliver hydrogen to vehicles. The overall investment cost for this infrastructure, worldwide, is likely to be in the trillions of US dollars. Overall, the retail price of hydrogen for transportation users, reflecting all feedstock, capital and operating costs, appears likely to remain well above USD 1.00/L of gasoline equivalent for the foreseeable future.

Given the advantages of ICE vehicles and existing infrastructure, it is unlikely, in the absence of very strong policy interventions and financial support from governments around the world, that market forces alone will be sufficient to deliver a significant shift from an ICE/petroleum system to an FCV/hydrogen system. Apart from issues surrounding the readiness and cost of fuel cell systems and hydrogen storage systems on vehicles, a central issue is that the development of an hydrogen infrastructure will be heavily dependent on the demand for hydrogen in transport,

and the demand for hydrogen in transport will be equally heavily dependent on the availability of the appropriate hydrogen infrastructure.

The BLUE Map scenario envisages a slow build-up of hydrogen infrastructure and FCV growth is assumed to reach only 25% of global LDV sales by 2050.

Electricity

Most of the electricity currently used in transport is used in passenger rail systems. Electricity's share of transport fuel across all modes worldwide is less than 1%. But electricity is likely to play an increasing role in the transport sector as in other sectors, particularly in a low CO₂ future. Electricity could be used to help power many types of vehicles, particularly cars, some types of trucks and most rail systems. However battery limitations may result in only limited use of electric power in long-haul trucks, ships and aircraft. In the ETP BLUE scenarios, electricity use increases dramatically over time, mainly from its increased use by electric and plug-in hybrid LDVs.

If electricity can be produced with low net GHG emissions and if electricity storage systems on vehicles improve, it may be possible to decarbonise transport progressively. The extent of this decarbonisation will depend on the availability of low-GHG electricity, technological developments in vehicles and storage systems such as batteries, and shifts to transport modes and vehicle types that can use electricity as a fuel. In the low-carbon ETP BLUE scenarios, electricity contributes between 15% and 25% of transport energy use by 2050.

Comparison of fuels

The characteristics of a range of fuels are summarised in Table 2.2. This analysis is no more than indicative as, for example, some characteristics can vary by region. But it seeks to convey a broad assessment of the advantages and disadvantages of different fuels. Petroleum fuels, for example, do quite well in nearly every category except GHG emissions. A number of other fuels do well in several categories except their availability for vehicles and their compatibility with today's ICE technologies.

One fuel that does reasonably well across all categories is cane ethanol, given its low production cost, expanding distribution infrastructure, compatibility with today's vehicles and good GHG characteristics. Only three types of fuels can deliver very low GHG emissions: ethanol, advanced biofuels, and electricity or hydrogen from low-GHG life-cycle feedstocks. For biofuels, the impacts of land-use change are not included in this table. These can, in some cases, be large enough to move a low GHG fuel into the very high GHG category.

Fuel cost comparisons

The cost of producing fuels can vary considerably both over time and in different regions, depending on factors such as the local market price of inputs (for example feedstocks) and the scale of production. The market price of fuels can vary even

Table 2.2 ▶ Comparison of the characteristics of various fuels

Fuel	Energy density	Production cost with oil at USD 100/bbl	Distribution infrastructure	Current production and retail availability for vehicles	Compatibility with existing ICE vehicles	Typical GHG emissions
Gasoline	High	Moderate	Complete	Complete	Complete	High
Distillate	High	Moderate	Complete	Complete	Complete	High
Jet fuel	High	Moderate	Complete	Complete	Complete	High
HFO	High	Moderate	Complete	Complete	Complete	High
CTL diesel	High	Moderate-high	Compatible with existing	Very low	Complete	Very high (high with CCS)
GTL diesel	High	Moderate-high	Compatible with existing	Very low	Complete	High (even with CCS)
Grain ethanol	Medium	Moderate-high	Partial	Low-moderate	Partial	Moderate-high
Cane ethanol	Medium	Low-moderate	Partial	Low-moderate	Partial	Low
Advanced ligno-cellulosic ethanol	Medium	High	Partial	None	Partial	Low
Oil-seed biodiesel	High	Moderate-high	Partial	Low-moderate	Partial	Moderate
Advanced BTL diesel	High	High	Compatible with existing	None	Complete	Low
CNG	Low	Low-moderate	Partial	Very low	Requires conversion	Moderate-high
LPG	Low	Low-moderate	Partial	Very low	Requires conversion	Moderate-high
Methanol from NG	Low	Moderate	Very low	Very low	Requires conversion	Moderate-high
DME from NG	Medium	Moderate	Very low	Very low	Requires conversion	Moderate-high
H ₂ from fossil sources	Low	Moderate	Very low	Very low	Requires conversion	Moderate-high
H ₂ from renewable sources	Low	High	Very low	None	Requires conversion	Very low
Electricity/fossil	Low	Low	Widespread	Very low	Incompatible	Moderate-high
Electricity/renewable	Low	Moderate	Widespread	Very low	Incompatible	Very low

Notes: Table classifications are indicative, based on current characteristics and estimates, and apply only to near term. There may be situations and regions in which these classifications do not apply. Production cost characterisations are based on analysis presented later in the chapter, and for hydrogen/electricity, these take into account the efficiency of the vehicles that would be most likely to use these fuels. For hydrogen compatibility with current vehicles, "requires conversion" relates to use in ICE vehicles. Hydrogen is, in practice, more likely to be used in FCVs.

Source: IEA analysis.

more, since it is subject not only to variations in production costs but also to market forces such as supply and demand, the quality of competition in the market, and local subsidies or taxes.

The fuel costs presented in this chapter have been calculated by the IEA using a bottom-up engineering approach based on the information contained in several literature sources.² Fuel production costs have been broken into their major cost components, each of which has been costed on the basis of information available publicly and in the relevant literature. The analysis takes into account potential variations in input costs and prices, and the way in which these could affect the final cost of producing fuels. The results are summarised here. A full report on this topic is forthcoming.

Main assumptions in the cost analysis

The analysis presented here accounts for most of the major costs involved in producing fuels and delivering them to the point of refuelling vehicles. This includes:

- **Conversion efficiency:** the efficiency of the conversion from primary energy to final transport fuel, which affects the amount of primary energy input required per unit output.
- **Feedstock/fuel yields:** the yield of the primary biomass material used as feedstock (where appropriate).
- **Cost of capital:** the cost of setting up a plant, making assumptions on the evolution of the costs of equipment, facilities, materials and personnel.
- **Operating and maintenance (O&M) costs,** often assumed to be annually around 10% of the cost of capital.
- **The market price of input streams** some of which, such as methanol, are assumed to be influenced by oil prices, and others of which, such as the enzymes required for the hydrolysis of starch and cellulose are assumed not to be influenced by oil prices.
- **The market price of electricity,** affected by assumptions on its linkage with oil prices.
- **The market price of primary energy inputs,** *i.e.* feedstocks, affected by assumptions made on its linkage to oil prices.
- **The cost of transporting fuel** to the distribution network, different for each fuel and assumed unaffected by changes in oil prices and costs of equipment, facilities, materials and personnel.
- **The cost of fuel storage and refuelling,** which is fuel-specific and assumed to remain constant over time.

2. Bon, 2007; Booth *et al.*, 2005; CHOREN Industries, 2007; EngineeringNews, 2007 and 2008; Geertsema, 2005; GreenCarCongress, 2006; IEA, 2004, 2005 and 2008c; IEA CIAB, 2006 and 2008; Igathinathane *et al.*, (2004) IHS; Kiener, 2008; McAloon *et al.*, 2000; McLaughlin *et al.*, 1996; OECD, 2005; Reuters, 2008; Ritschel *et al.*, 2007; Robertson, 1999; Singh *et al.*, 2001; UDOP; UDSA; USDA, 2006; and Woods *et al.*, 2003, amongst others.

- **The revenues derived from co-products** associated with the fuel production process, taking into account linkages to oil prices.

The costs of energy, feedstocks and other input streams are, themselves, affected by market price fluctuations. The analysis attempts to account for these potential effects. For example, the amount of oil and oil products used as inputs into other fuels has been estimated, and several scenarios have been run assuming different oil prices, in order to see what impact that would have on the cost of producing other fuels. Similar scenarios were made varying other input costs, particularly the cost of crops as feedstocks into biofuels. This scenario approach has also been extended in other ways, including looking at scale effects, providing separate estimates for near-term fuels and those produced farther into the future. Future cost estimates seek to ensure that all expected reductions or other changes in costs, mainly related to technology improvements, are accounted for. Such costs depend, among other things, on the average plant size and might be expected to apply in or around 2030 or sooner if a significant development of the fuel pathway has taken place. Some future cost reductions, such as those coming from technology learning and optimisation, would be dependent on the rate of expansion in the production of the relevant fuel. If a fuel is not commercially introduced, costs might not come down very quickly.

Fuel cost analysis results

Key results of the fuel cost analysis are presented below for three different cases. These cases explore costs of various fuels under different assumptions of underlying oil prices and the potential impacts of these oil prices on the input costs for other fuels, in both the near and longer term. The three cases are:

Case 1: Oil at USD 60 real/bbl, “base” effect of the oil price on the cost of equipment, facilities, materials and personnel for all other fuels.

- In this case the estimates of costs of various input fuels (e.g. coal and natural gas) are fixed at values they tended to assume over the past decade, especially when oil prices were close to USD 60/bbl (a value corresponding to about USD 9.8/GJ). Specifically, coal prices are assumed to correspond to USD 2.8/GJ, natural gas prices to USD 6.6/GJ and woody biomass prices to USD 4.2/GJ. Corn is assumed to cost more than woody biomass at roughly USD 7.2/GJ, and cane is assumed to be cheaper at USD 2.8/GJ. Vegetable oil prices are assumed to be about USD 15.3/GJ.
- The costs of equipment, facilities, materials and personnel are fixed at values estimated for an oil price of USD 60/bbl, or as estimated in various data sources during periods when oil was in this price range.

Case 2: Oil at USD 120 real/bbl, no correlation between this price and other feedstock and energy commodity prices; however, the higher oil price affects the cost of equipment, facilities, materials and personnel.

- In this case oil prices are assumed to have no direct influence on the price of other feedstocks and energy commodities like coal or natural gas.

- Changes in the oil price have been considered as a driver for the costs of equipment, facilities, materials and personnel. The relationship amongst these parameters has been estimated according to the information that can be derived from the variation of the downstream capital cost index, correcting it in order to account for the effects that are not specific to the downstream energy industry.

Case 3: Oil price of USD 120 real/bbl, with oil prices correlated to other fossil energy prices and impacting other feedstock and input prices; further (like Case 2), oil price affects the cost of equipment, facilities, materials and personnel linked to the price of oil.

- In this case oil prices are assumed to have a direct influence on the price of other feedstocks and energy commodities like coal or natural gas. Fossil commodity prices evolve according to historic trends. Biomass-based commodity prices are assumed to be influenced at a 20% elasticity by the price change of oil (starting from values considered in Case 1), with the aim of simulating direct impacts;
- Changes in the oil price have been considered as a driver for the costs of equipment, facilities, materials and personnel on the same basis as in Case 2.

For each case, a near-term and long-term set of estimates have been made as follows:

- In the near term (e.g. 2010-2015), the estimated production costs by fuel type at large volume production are shown, broken into fixed (capital, operating and maintenance, non-energy inputs such as enzymes, fuel transport and storage costs) and variable costs (feedstock costs, energy input streams, electricity).
- For the long term (e.g. 2020-2030), the estimated lowest fixed and variable production costs of fuels that might ultimately be achieved – *i.e.* once technologies mature and optimisation is achieved – are shown. These values depend in part on learning rates and cumulative production. Thus, the faster that high levels of cumulative production of a specific fuel are reached, the faster costs decline. This makes estimating the date when “long-term” costs are achieved especially difficult to determine.

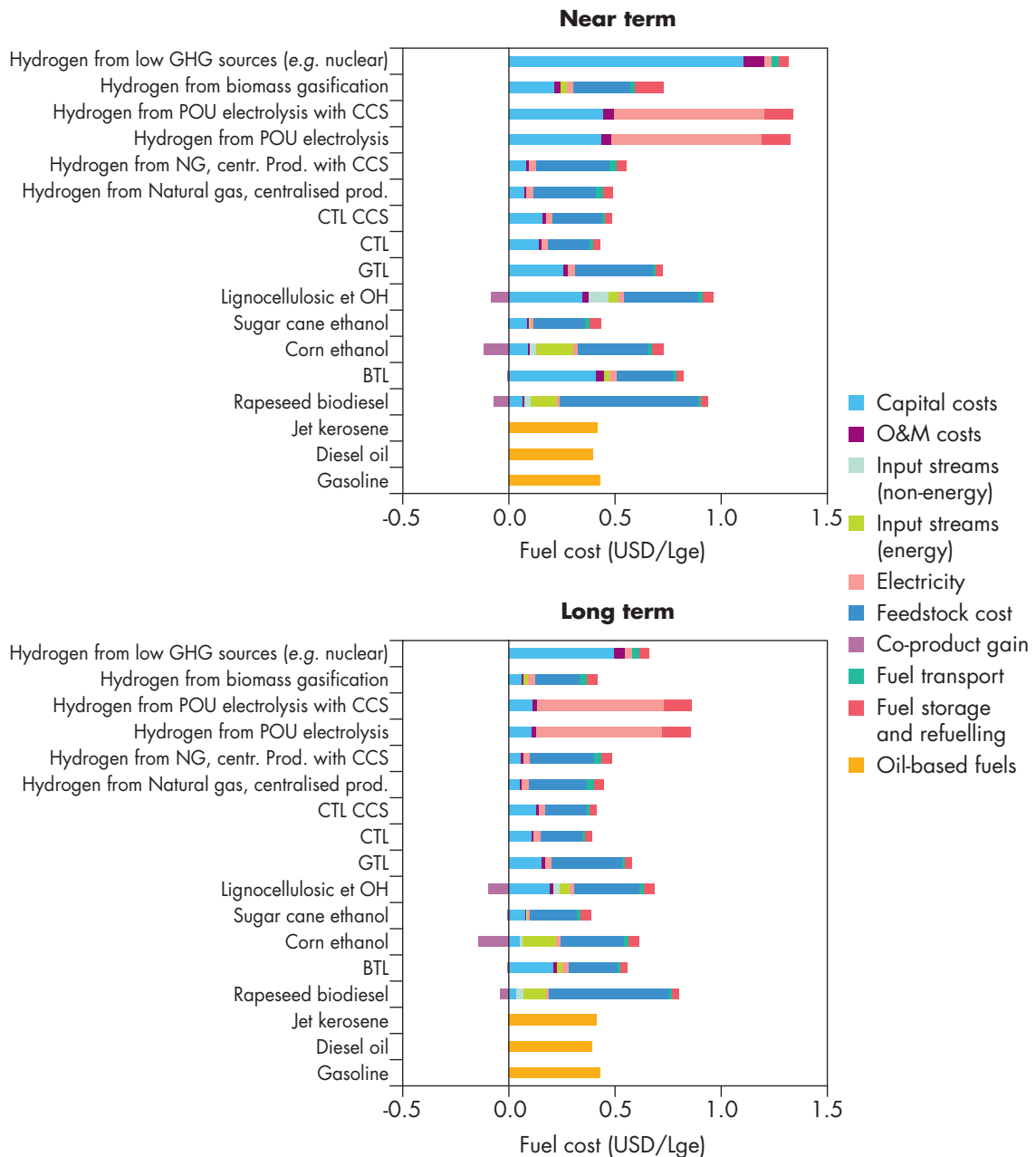
Results for Case 1 are presented in Figure 2.15, with key estimates also shown in Table 2.3.

Similar estimates are shown for Case 3 in Table 2.4, reflecting higher oil prices than Case 1 and significant influence of oil prices on feedstock costs and factor inputs for other fuels. Case 2 is not shown separately, but all three cases are compared in Figure 2.16 using long run cost estimates.

Comparative analysis of the results

These cases show that only a few fuel production pathways are cost competitive with gasoline or diesel, in either the near term or the longer term, when oil prices are at USD 60/bbl. Only sugar cane ethanol, even at the small production scale of 4 GJ per year, and very large CTL plants producing 70 GJ of fuel per year, whether or not equipped for CCS (at a cost of USD 25/tonne of CO₂ sequestered)

Figure 2.15 ▶ Fuel cost estimates with oil at USD 60/bbl, fixed feedstock prices and no oil price effects on other input costs



Key point

If oil prices stay at USD 60/bbl, hydrogen from biomass gasification, CTL and sugar cane ethanol are likely to be the most cost competitive with oil-based fuels in the long term.

Table 2.3 ▶ Key assumptions characterising the fuel pathways considered: case 1

	Production capacity (million Lge/y)		Capital costs (USD/GJ)		O&M costs (USD/GJ)		Fuel transport (USD/GJ)	Fuel storage and refuelling (USD/GJ)
	Near term	Long term	Near term	Long term	Near term	Long term	Near and long term	Near and long term
Rapeseed biodiesel	125	750	1.9	1.0	0.2	0.1	0.5	1.1
Sugar beet ethanol	125	750	5.1	2.9	0.5	0.3	0.7	1.7
Sugar cane ethanol	125	750	2.6	2.3	0.3	0.2	0.7	1.7
Corn ethanol	125	750	2.7	1.5	0.3	0.2	0.7	1.7
Wheat ethanol	125	750	3.8	2.1	0.4	0.2	0.7	1.7
CTL	2 200	7 000	4.2	3.3	0.4	0.3	0.5	1.1
CTL CCS	2 200	7 000	4.8	3.9	0.5	0.4	0.5	1.1
GTL	1 800	5 500	7.7	4.7	0.8	0.5	0.5	1.1
BTL	125	750	12.3	6.3	1.2	0.6	0.5	1.1
Ligno-cellulosic ethanol	125	750	10.3	5.8	1.0	0.6	0.7	1.7
H ₂ from natural gas, centralised production	1 560	1 560	2.1	1.6	0.4	0.3	1.1	1.6
H ₂ from natural gas, centralised production with CCS	1 560	1 560	2.5	1.7	0.4	0.3	1.1	1.6
H ₂ from point of use electrolysis			12.9	3.2	1.7	0.7		4.6
H ₂ from point of use electrolysis with CCS			13.3	3.4	1.7	0.7		4.6
H ₂ from coal	1 000	1 000	1.9	1.5	0.3	0.3	1.1	1.6
H ₂ from coal with CCS	1 000	1 000	2.0	0.0	0.3	0.0	1.1	1.6
H ₂ from biomass gasification	130	750	6.4	1.8	0.6	0.3	1.1	1.6
H ₂ from low GHG sources (e.g. nuclear)	130	1 000	32.9	14.9	3.4	1.6	1.1	1.6

Table 2.4 ► Key assumptions characterising the fuel pathways considered: case 3

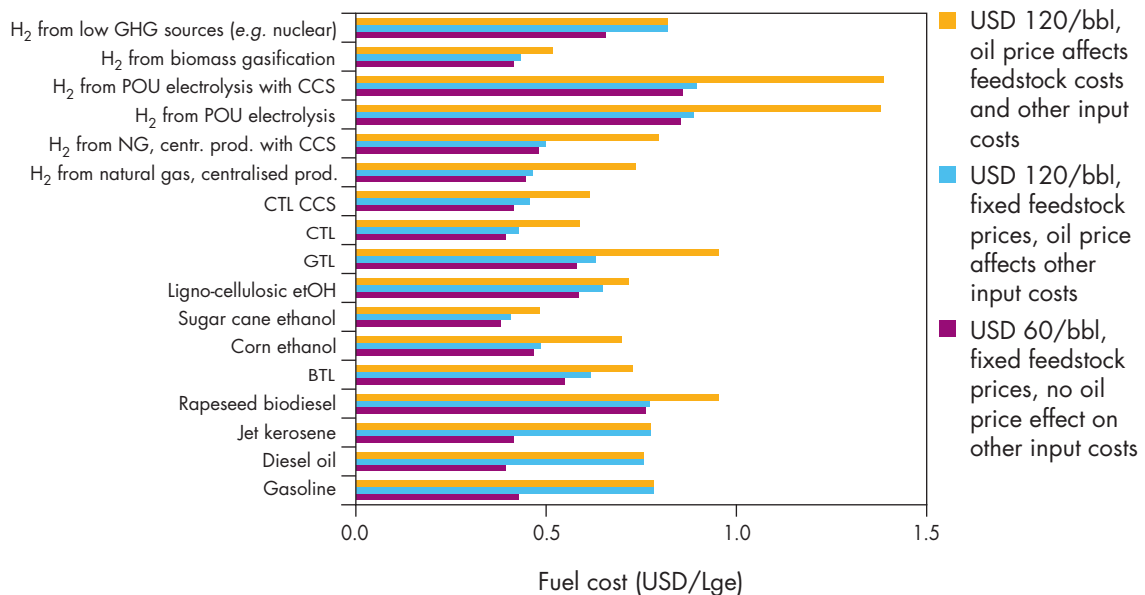
	Production capacity (million Lge/y)		Capital costs (USD/GJ)		O&M costs (USD/GJ)		Fuel transport (USD/GJ)	Fuel storage and refuelling (USD/GJ)
	Near term	Long term	Near term	Long term	Near term	Long term	Near and long term	Near and long term
Rapeseed biodiesel	125	750	2.6	1.3	0.3	0.1	0.6	1.5
Sugar beet ethanol	125	750	6.7	3.9	0.7	0.4	0.9	2.3
Sugar cane ethanol	125	750	3.4	3.1	0.3	0.3	0.9	2.3
Corn ethanol	125	750	3.6	2.0	0.4	0.2	0.9	2.3
Wheat ethanol	125	750	5.0	2.8	0.5	0.3	0.9	2.3
CTL	2 200	7 000	5.5	4.3	0.5	0.4	0.6	1.5
CTL CCS	2 200	7 000	6.3	5.1	0.6	0.5	0.6	1.5
GTL	1 800	5 500	10.2	6.2	1.0	0.6	0.6	1.5
BTL	125	750	16.3	8.3	1.6	0.8	0.6	1.5
Ligno-cellulosic ethanol	125	750	13.7	7.7	1.4	0.8	0.9	2.3
H ₂ from natural gas, centralised production	1 560	1 560	2.8	2.1	0.5	0.4	1.5	2.1
H ₂ from natural gas, centralised production with CCS	1 560	1 560	3.3	2.3	0.5	0.4	1.5	2.1
H ₂ from point of use electrolysis			17.2	4.3	2.3	1.0		6.0
H ₂ from point of use electrolysis with CCS			17.6	4.5	2.3	1.0		6.0
H ₂ from coal	1 000	1 000	2.6	2.0	0.5	0.4	1.5	2.1
H ₂ from coal with CCS	1 000	1 000	2.7	0.0	0.5	0.0	1.5	2.1
H ₂ from biomass gasification	130	750	8.5	2.4	0.8	0.4	1.5	2.1
H ₂ from low GHG sources (e.g. nuclear)	130	1 000	43.7	19.8	4.6	2.2	1.5	2.1

can compete in the near term. Hydrogen production from biomass gasification eventually also approaches cost competitiveness.

The cases also underline the importance of commodity prices for the cost competitiveness of each fuel pathway (Figure 2.16). With oil prices at USD 120/bbl and other commodity prices unchanged, several additional alternative fuel pathways become cost-competitive, including corn ethanol (4 GJ per year units) and hydrogen produced from natural gas in centralised plants producing 950 GJ per year with or without CCS. In the long run, when production capacities are assumed to be five to six times larger for biomass-based fuels and collectively to exceed 200 GJ per year for CTL projects and 175 GJ per year for GTL projects, nearly all alternative fuels become competitive except certain hydrogen pathways.

When commodity/oil price linkages similar to those observed in the past decades are taken into account, together with some interactions between feedstock prices, prices for many finished fuels rise in parallel with oil prices. Only a limited number of options, including large CTL, CTL with CCS, and sugar cane ethanol, are cost-competitive in the near term. In the long term, BTL biodiesel, corn ethanol, ligno-cellulosic ethanol and hydrogen from centralised natural gas plants and biomass gasification also approach the cost-competitiveness hurdle.

Figure 2.16 ▶ Results of the three cases



Key point

Oil price increase has a significant effect on alternative fuels for transportation.

This analysis suggests that large CTL plants offer the cheapest alternative to oil-based fuels, and an alternative that is cost-effective at oil prices above USD 60/bbl. This may be an attractive option, especially in coal-rich areas of the world such as China, subject to the resolution of concerns over the long-term (up to 10 years) construction times for CTL plants and associated high construction costs, which

are assumed to be overcome with experience and learning. Sugar cane ethanol production may also be attractive in countries such as Brazil, where large-scale multi-purpose sugar/ethanol mills already produce competitively priced ethanol. But the low feedstock costs achievable in Brazil may be difficult to replicate in many other locations.

The cost of producing fuel from other pathways is highly sensitive to changes in feedstock and energy commodity prices. For GTL and hydrogen produced from natural gas, natural gas price rises significantly increase fuel production costs. This is consistent with the observation that GTL plants are cost competitive today only in areas with stranded gas reserves that are accessible at prices significantly below the average market gas price. The analysis suggests that oil prices would need to be at least 50% higher than natural gas prices on an energy basis to make GTL cost-competitive.

Other fuel pathways are unlikely to be cost-competitive with petroleum-based fuels in the near term even with oil at USD 120/bbl, although BTL and cellulosic ethanol could approach competitiveness in the longer term.

BTL fuels may become a viable option at USD 120/bbl, especially if technology learning and economies of scale produce longer term price reductions. But the price of the biomass required for their production is uncertain. Relatively low-cost biomass is an essential requirement for cost-competitive BTL fuels and cellulosic ethanol.

The size of conversion facilities is important for BTL economics. The analysis presented here reflects the assumption that in the near term, BTL plants would be similar in size to other installations producing biofuels, and significantly smaller than CTL or GTL plants. Increasing BTL plant size depends on the availability and cost of providing sufficient biomass feedstocks. This may, in turn, require the contribution of technologies aimed at increasing the energy density of feedstocks, such as pelletisation or heat drying. Similar considerations apply to the size of cellulosic ethanol plants.

If new fuels are to make a significant contribution to cutting CO₂ emissions, the best options appear to be hydrogen, electricity and biofuels. No other types of fuels have low enough carbon content to deliver substantial CO₂ reductions.

Review of the GHG characteristics of different fuels

GHG emission characteristics

The GHG emissions associated with different fuels depend on the way in which those fuels are produced. To compare the GHG impacts of fuels, it is necessary to take into account all the emissions generated from their production, transport and storage, as well as the emissions associated with their use in vehicles on the basis of a full life-cycle analysis (LCA).

Any LCA of biofuels, for example, needs to consider, amongst other things, the emissions associated with the production of fertilisers and other agricultural

activities, including emissions from the use of machines or those associated with the need for irrigation. It also needs to take account of the emissions associated with the use of fossil and renewable fuels in the industrial processing of the biofuel feedstocks, and the emissions associated with the construction and operation of the plants producing the fuels, as well as the emissions entailed in the final combustion of fuels. These emissions need to be offset by the amounts of CO₂ taken in from the atmosphere by the biomass in its growth phase.

LCAs should also account for co-products, including potential GHGs other than CO₂. For example, NO_x are a product of the application of nitrogen fertilisers and are also associated with the biofuel manufacture process. Given the high uncertainty associated with the NO_x emission factors in different climatic conditions, for instance, all assessments that do not address rather specific biofuels production sites bear a certain degree of approximation. Similarly, the effects of land-use change should be considered, including any CO₂ emissions that are produced when the stock of carbon contained in the soil and the covering vegetation are depleted as a result of changes in land use. Much more research is needed on these types of issues. The range of opportunities to grow genuinely low-GHG biofuels may be much narrower than is typically assumed today.

LCAs also need to be carried out for other fuels, taking into account the specifics of the industrial processes required for their manufacture, including the energy and materials requirements and the emissions associated with them, as well as emissions due to the extraction of the primary feedstocks needed for their synthesis.

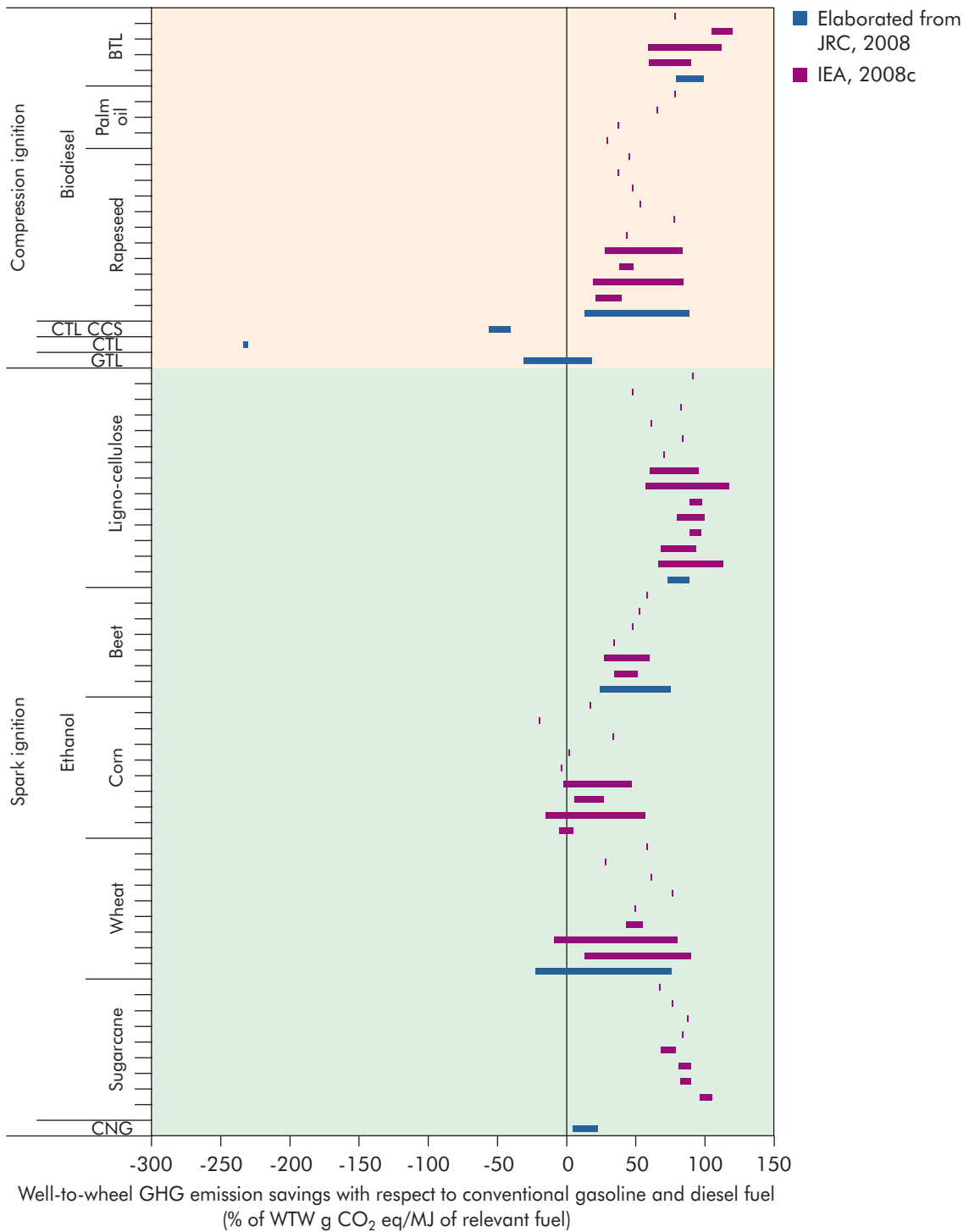
Significant uncertainties can surround the LCAs of biofuels and other alternative fuels. In the case of biofuels, the degree of uncertainty is larger, since some effects such as NO_x emissions are strongly dependent on soil characteristics and weather conditions. Other parameters, such as the release of CO₂ and other GHGs from direct and indirect land-use change, are extremely difficult to assess because they depend on the evolution of significant parts of the agricultural sector. Therefore, they are affected by such aspects as food demand and agricultural trade regulations.

Figure 2.17 shows a summary of estimates of well-to-wheel GHG emissions for a number of fuels. For non-biofuels, the data are taken from JRC (2008). For biofuels, the Figure includes data from a recent IEA comparison of other studies (IEA, 2008c).

Figure 2.18 shows mid-point estimates of well-to-wheel GHG emissions derived from Figure 2.17. These estimates are used to determine the carbon intensity of different fuels in the analysis throughout this report. Figure 2.20 also shows the well-to-tank and tank-to-wheel emission components of the total well-to-wheel emissions.

Figures 2.17 and 2.18 highlight that fuels have very different characteristics with respect to the emissions of GHGs. CTL fuels produced without CCS generate much higher levels of emission on a well-to-wheels basis than conventional petroleum fuels. Fuels produced from oil sands are likely to generate similar levels of emissions, given the additional GHGs produced in their extraction. Fuels produced from heavy oils, not described in this analysis, would be likely to generate similar levels of emission. Using nuclear heat to provide the energy needed for

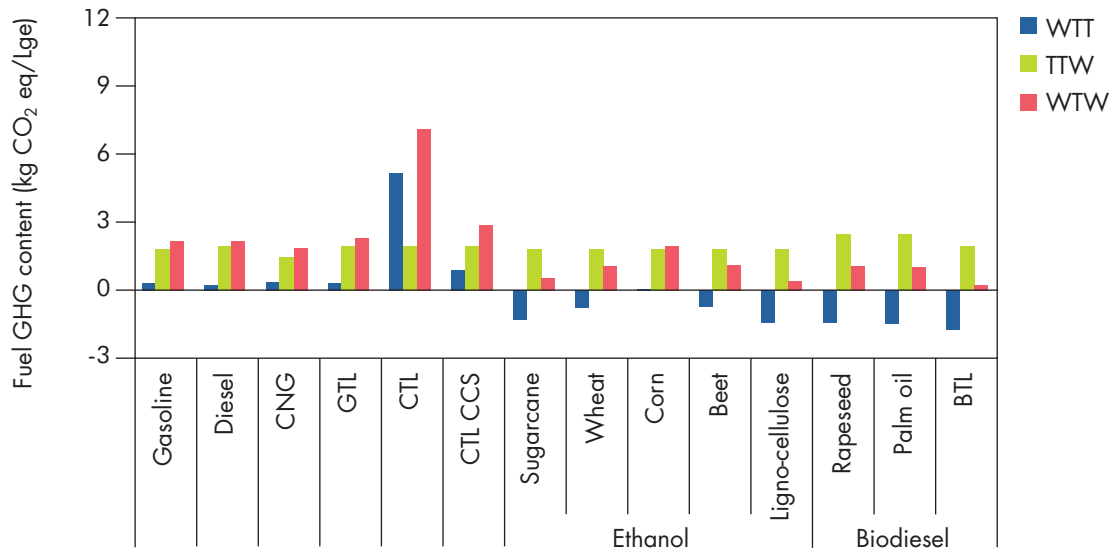
Figure 2.17 ► Well-to-wheel emissions ranges (excluding land-use change) for a set of alternative fuels, compared with the emissions of a gasoline-powered vehicle



Sources: Various.

Key point

BTL, ligno-cellulose and sugar cane fuels have the highest GHG savings of biofuels.

Figure 2.18 ▶ Mid-point estimate of GHG emissions per litre of gasoline equivalent

Sources: Various

Key point

Mid-point estimates of GHG emissions per litre of gasoline equivalent are lowest for BTL, ligno-cellulose and sugar cane fuels.

the conversion processes, or applying CCS to the fuel production process, would reduce the emissions associated with these fuels, and those associated with GTL fuels, significantly to around the same levels as biofuels (such as corn ethanol and wheat ethanol). These would produce similar levels of emission as CNG except where their manufacture used a significant amount of biomass as primary energy source.

Biofuel derived from vegetable oil, as well as corn and wheat-based ethanol when they are produced using biomass as a primary energy source (rather than just as a feedstock), would cut GHG emissions on a well-to-wheel basis by about half of that of conventional fossil fuels. For even deeper cuts in emissions, biofuels would need to be produced from sugar cane and ligno-cellulosic feedstocks.

The performance of biofuels could be significantly overestimated since the impacts of land-use change, nitrogen fertilisers, and perhaps other related dynamics (for instance, to different levels of rainfall) are not well reflected in the estimates. In general, there is a need for studies to derive better and more comprehensive estimates of the well-to-wheel GHG emissions of fuels. These should better reflect issues associated with land-use change, nitrogen cycles and other complexities, and better incorporate a range of pollutants that can impact the climate such as black carbon, sulphates, ozone and others. It would also be very useful to undertake studies to identify the GHG impacts of average current practices, best current practices, and potential improvements in the future. Inherent differences in GHG emissions from production in various climates or geographic regions also need to be better understood.

GHG mitigation costs of fuels

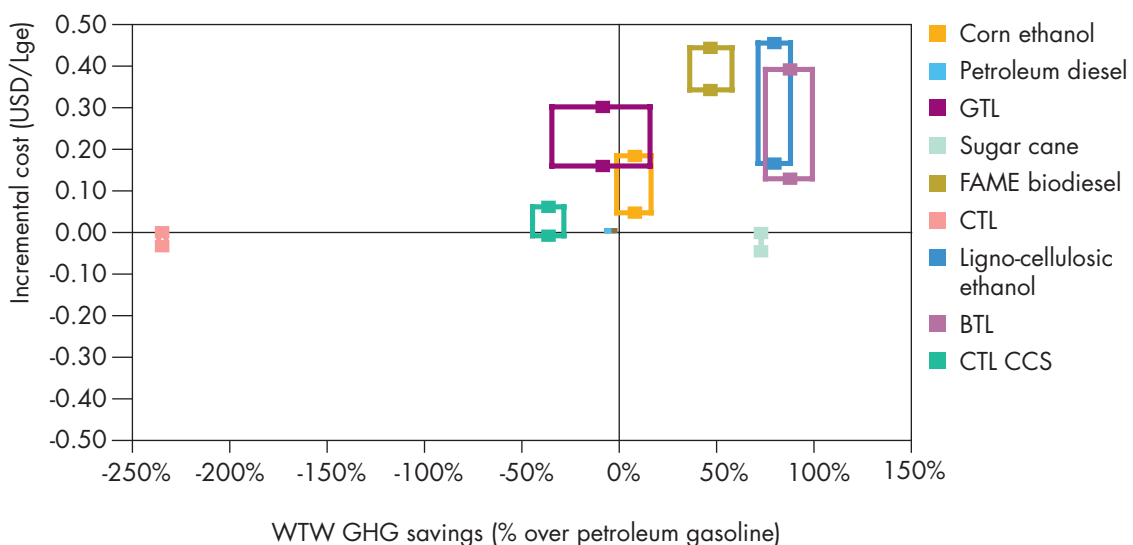
Notwithstanding the uncertainties, combining the cost and GHG estimates for various fuels can give a broad measure of the cost of reducing GHG emissions associated with each alternative fuel pathway. The same set of information can be used to evaluate the effect of carbon prices on the relative costs of different fuels.

Figures 2.19 and 2.20 illustrate the incremental cost of alternative fuels as a function of their CO₂ saving potentials. The figures refer to two oil price scenarios: USD 60 and USD 120/bbl. They have been evaluated on the basis of the fuel characteristics with respect to well-to-wheel GHG emissions using the mid-point estimates reported in Figure 2.18, as well as the variation ranges shown in Figure 2.17. They also take into account the fuel production costs – as described in Cases 1 and 3 of the analysis – and include estimates for the near term and long term.

The same results, combined together and expressed in terms of costs (or savings) per tonne of CO₂ displaced on a well-to-wheel basis are shown in Figure 2.21.

The figures show that sugar cane ethanol and CTL fuels are expected to offer the lowest-cost CO₂ reduction alternative to petroleum fuels both in the short and long term. They are already almost competitive and remain the most competitive options for the longer term, largely as a result of further cost reductions coming from optimisation, learning and increases in the typical plant size. Sugar cane ethanol and CTL fuels produced without CCS, however, have strikingly different characteristics with respect to conventional fuels in terms of their GHG emission reduction potential (notwithstanding the caution required for land-use change in the case of sugar cane ethanol). Taking

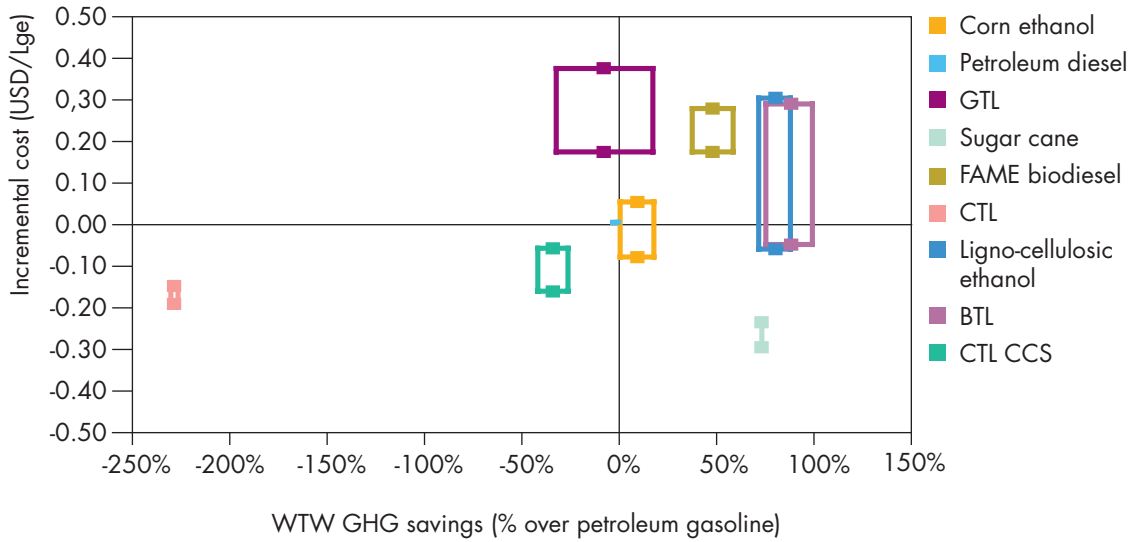
Figure 2.19 ► Incremental cost of alternative fuels as a function of their CO₂ saving potentials (USD 60/bbl)



Key point

At USD 60/bbl, only CTL and sugar cane ethanol are competitive with oil, with very different GHG consequences.

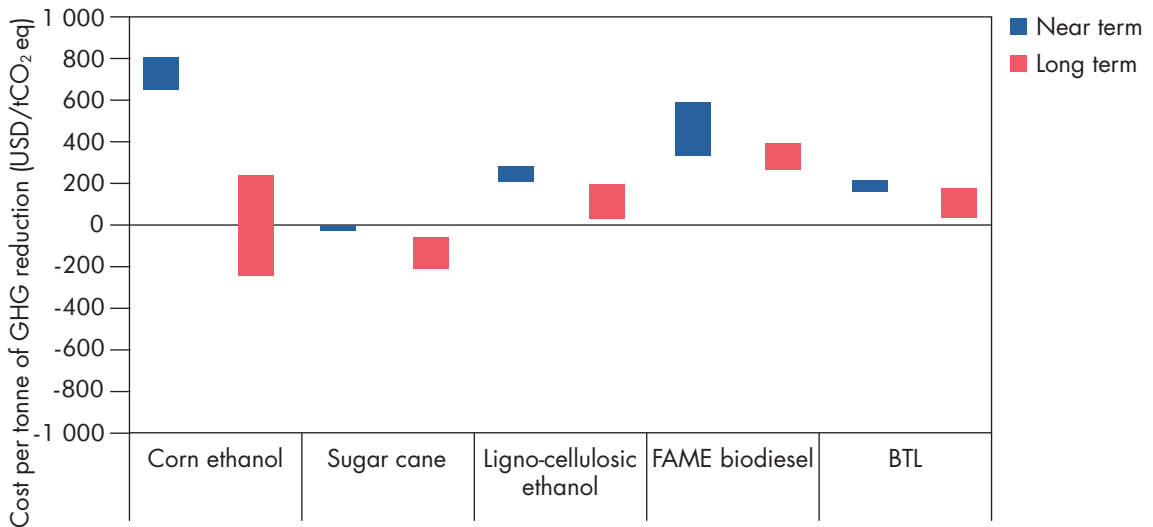
Figure 2.20 ▶ Incremental cost of alternative fuels as a function of their CO₂ saving potentials (USD 120/bbl)



Key point

As oil price increases, first- and second-generation biofuels become a cost-effective solution.

Figure 2.21 ▶ Cost per tonne GHG saved, well-to-wheel



Key point

While corn ethanol has the lowest cost per tonne CO₂ displaced in the short run, it trails sugar cane, BTL, ligno-cellulosic ethanol and FAME biodiesel in the long run.

action to move toward a low-emission future inevitably involve a strong choice for either one option or the other.

Second-generation biofuels also lead to low emissions but they deliver GHG savings at higher cost compared to sugar cane ethanol. With oil at USD 60/bbl in the near term, BTL fuels and ligno-cellulosic ethanol are expected to deliver CO₂ reductions at a cost close to USD 200/t. Nevertheless, if oil prices rise to USD 120/bbl, some of these GHG savings could even be achieved at a negative cost.

Ethanol derived from cereals is characterised by relatively low CO₂ reduction potential. This is why GHG mitigation costs vary widely, ranging from USD 800/t CO₂ eq in the short term with oil at USD 60/bbl to zero or less in the long term if oil costs USD 120/bbl.

All biofuels but corn ethanol (in the short term) perform better than conventional biodiesel. Even if the wide variations in biodiesel feedstock prices seen in recent years are not reflected in this comparison, FAME biodiesel leads to GHG mitigation at costs that always exceed USD 200/t. Given the importance of land-use change for vegetable oil feedstocks and the significant ongoing deforestation (notably in Southeast Asia), such an estimate is likely to be on the optimistic side.

Chapter 3 LIGHT-DUTY VEHICLES

Key findings

- ▶ In 2006, the 800 million light-duty vehicles (LDVs, including automobiles, light trucks, SUVs and mini-vans) around the world accounted for about 47% of transport energy use. The total stock of LDVs is expected to grow to at least 2 billion by 2050 and possibly much higher, depending especially on ownership trends in countries such as China and India.
- ▶ The fuel economy of LDVs has improved only slowly in many regions over the past two decades. The European Union and Japan have achieved much faster than average rates of improvement.
- ▶ In the future, there are excellent opportunities to cut fuel use and CO₂ emissions from LDVs. These include solutions to improve internal combustion engine (ICE) efficiency, vehicle hybridisation and the potential contribution of technologies such as electric or fuel cell vehicles (FCVs). Plug-in hybrid vehicles appear to offer a particularly attractive intermediate step on the way from ICE to pure electric vehicles (EVs).
- ▶ Although in the Baseline scenario LDV energy use doubles by 2050, in the BLUE Map scenario it is cut by more than 50% and reaches 10% below 2005 levels. Moreover, in the Baseline scenario, LDVs continue to use mainly petroleum fuels, whereas in the BLUE Map scenario about 80% of LDV fuel needs in 2050 are met from a combination of biofuels, electricity and hydrogen. This cuts CO₂ emissions from LDVs by 87% in 2050 compared to the Baseline scenario in that year, and 75% below 2005 levels. This is the deepest reduction of any transport mode in the BLUE scenarios.
- ▶ Although technologies to improve LDV efficiency can be expensive, when the fuel savings they provide are taken into account, many are low or even negative cost options. This is particularly true at higher oil prices and low discount rates. With oil at USD 120/bbl and using a low discount rate, virtually all near-term improvements to gasoline and diesel vehicles, through full hybridisation, are paid for by vehicle lifetime fuel savings. The cost-effective cumulative potential to improve new LDV fuel economy reaches 50% by 2030. Plug-in hybrids can also provide relatively low-cost CO₂ reductions in the near term, notably in areas with low GHG electricity generation. However, pure EVs and FCVs remain relatively expensive in the near term, even at a USD 120/bbl oil price.
- ▶ In the medium to long term (i.e. 2015-20 and beyond), as costs come down through RD&D, optimisation and learning, even EVs and hybridised FCVs may provide relatively low-cost GHG reductions (i.e. less than USD 100/tonne CO₂ eq. saved), at least at oil prices of USD 120/bbl or higher. FCV costs and their cost-per-tonne using hydrogen from low-GHG sources are estimated to be competitive with EVs, though important questions remain.

- ▶ Overall, the most promising pathway to significant GHG emission reductions in LDVs appears to begin with the full adoption of cost-effective incremental technologies for gasoline and diesel vehicles, then full hybridisation, then plug-in hybrids, and eventually either EVs or FCVs. Evolution along these lines may give EVs a natural advantage given the existence of the electricity grid system, and a clear transitional path from plug-in hybrids.
- ▶ Biofuels can also play an important role for ICE LDVs, with some cost-effective options available today (such as ethanol from sugar cane), and advanced biofuels becoming more cost-effective over time. However the role of biofuels for LDVs in BLUE Map begins to decline after 2030, given a strong shift toward electricity and hydrogen fuels. By 2050, most biofuels use in BLUE Map replaces diesel fuel for trucks, ships and aircraft.

Introduction and historical trends

Passenger light-duty vehicles (LDVs)

LDVs are primarily used for the transport of passengers, and include sedans, personal pick-up trucks, high-performance sports cars, mini-vans and sport utility vehicles (SUVs). Although definitions vary, LDVs are typically for personal use and therefore most have seven seats or less. Light commercial vehicles, though often of a similar size and nature to larger LDVs, are treated in the Mobility Model (MoMo) as freight vehicles, and are dealt with in Chapter 6.

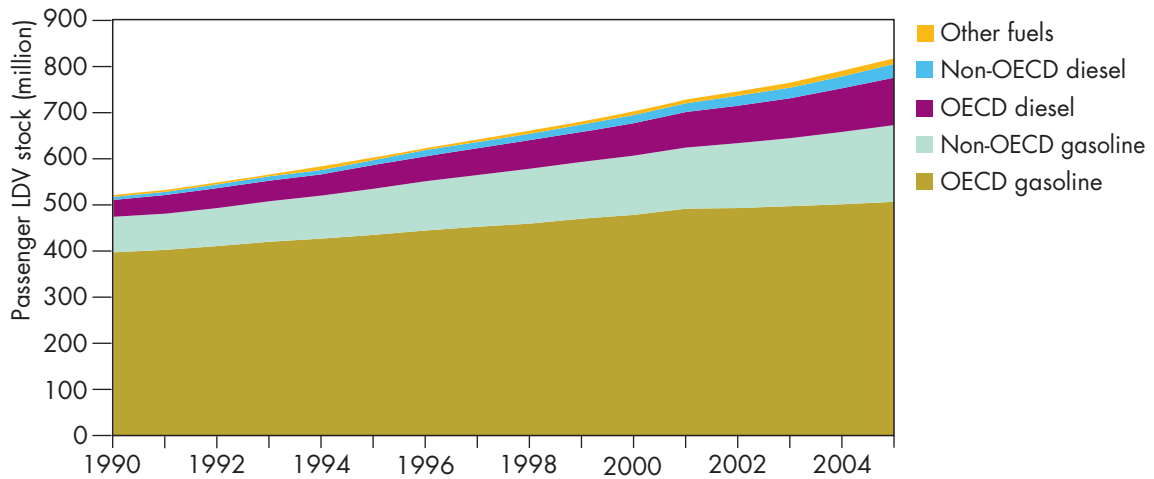
Almost all LDVs on the road today are powered by ICEs using either gasoline or diesel fuel (Figure 3.1). Even hybrid electric vehicles (HEVs) require an ICE and rely mainly on liquid petroleum fuels for primary energy.

LDV sales and shares by technology

ICEs powered by petroleum fuels have three particularly significant strengths:

- Their versatility and power, and notably their ability to respond rapidly to user needs.
- Their moderate cost compared to many alternatives.
- The outstanding merits of petroleum fuels in terms of energy density (energy per unit volume) and specific energy (energy per unit mass), as described in Chapter 2. Biofuels such as ethanol also have good energy density, but much lower than gasoline or diesel fuel.

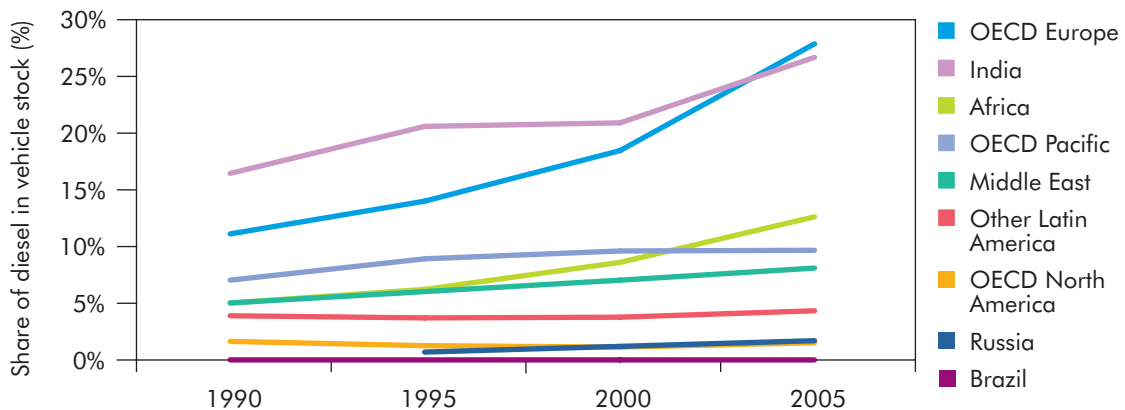
In many countries and regions, the proportion of LDVs powered by diesel engines has grown over time, partly as a result of improvements in the performance of diesel engines and also because of fuel-differentiated emission regulations

Figure 3.1 ▶ Number of passenger LDVs by region and fuel

Source: IEA Mobility Model database.

Key point

Dieselisation has grown rapidly in Europe, thanks to favourable taxation and regulation.

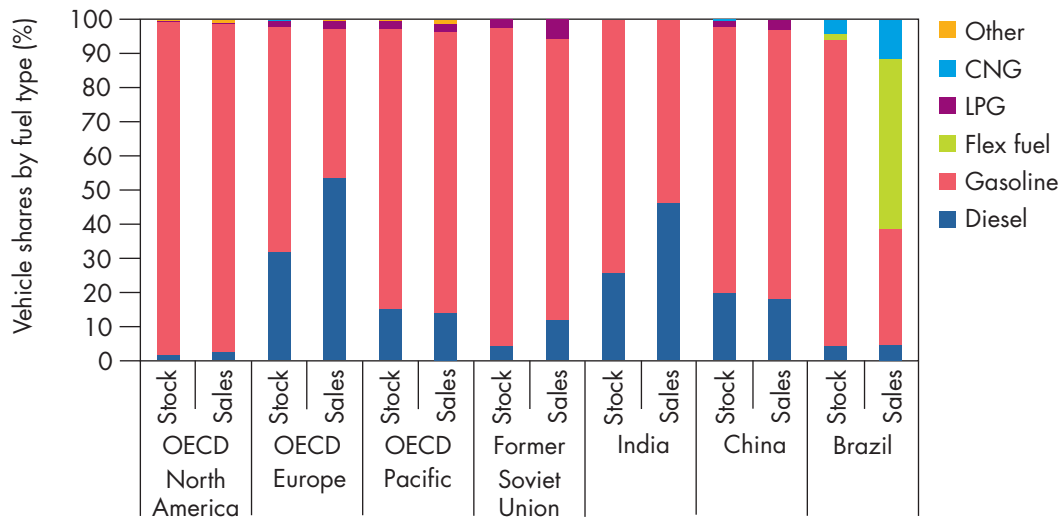
Figure 3.2 ▶ Share of diesel engines in LDV stocks in selected regions

Source: IEA Mobility Model database.

Key point

LDV diesel shares since 1990 have risen in most regions.

(Figure 3.2). Diesels are more cost-effective for long-distance journeys, given their greater efficiency than gasoline-powered engines. Diesel fuel savings, even in countries with higher diesel prices, can more than offset the higher purchase cost of the vehicles given their 25% to 30% efficiency advantage.

Figure 3.3 ▶ LDV sales and stocks shares by technology and region, 2005

Note: Stock and sales data are obtained as an average amongst the values of 2004, 2005 and 2006 from the comparative analysis of several sources in each region considered.

Source: IEA Mobility Model database.

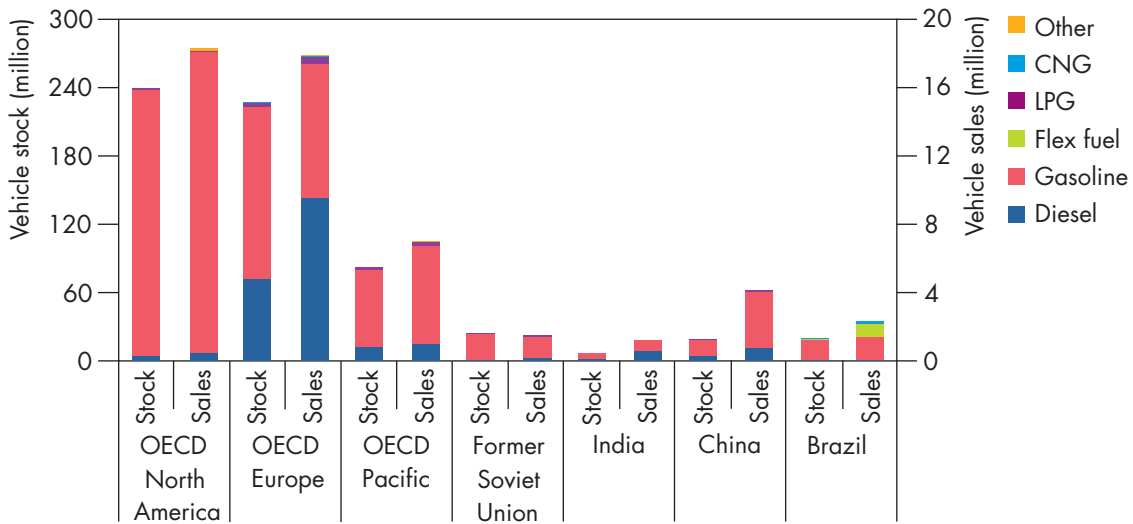
Key point

Gasoline and diesel vehicles dominate sales and stock of LDVs in most major LDV markets.

Over 80% of the worldwide stock of LDVs in 2005 was fuelled by gasoline (Figure 3.3). Except in Europe and parts of Asia, gasoline vehicles still represent 90% or more of all LDVs in most countries. But in some regions, diesel sales have grown to a level proportionately well above current stock shares. So stock shares in these regions are increasing. In 2005, France already had one of the highest diesel LDV sales shares in the world at just over 50%. Sales in France have since grown to 77% (in 2008). India leads the developing world with diesel LDV sale shares of over 25%.

Other fuel types include liquefied petroleum gases (LPG), compressed natural gas (CNG), biofuels such as ethanol and biodiesel, and electricity for EVs. The sales and use of vehicles running on these fuels is not significant despite widespread efforts around the world to promote alternative fuels, except in a few cases. Korea, for example, has a significant number of LPG vehicles and a few countries now have rising percentages of biofuel vehicles. As shown in Figure 3.3., Brazil leads the world in sales of ethanol-capable vehicles, with gasoline/ethanol flex-fuel vehicles accounting for about half of LDV sales in 2005, and rising rapidly.

In terms of numbers of vehicles, both stocks and vehicle sales are much higher in OECD countries than elsewhere (Figure 3.4). Although diesel shares are growing in a few regions (e.g. India), there continue to be far more diesel LDVs in OECD Europe than anywhere else. Far more LDVs of all types are sold and used in OECD North America and Europe than in other regions. This will change fairly rapidly in the years to come as increasing personal wealth in developing countries enables larger numbers of LDV purchases.

Figure 3.4 ▶ LDV stock and new registrations by technology and region, 2005

Note: Stock and sales data are obtained as an average amongst the values of 2004, 2005 and 2006 from the comparative analysis of several sources in each region considered.

Source: IEA Mobility Model database.

Key point

Total LDV diesel sales are highest in OECD Europe.

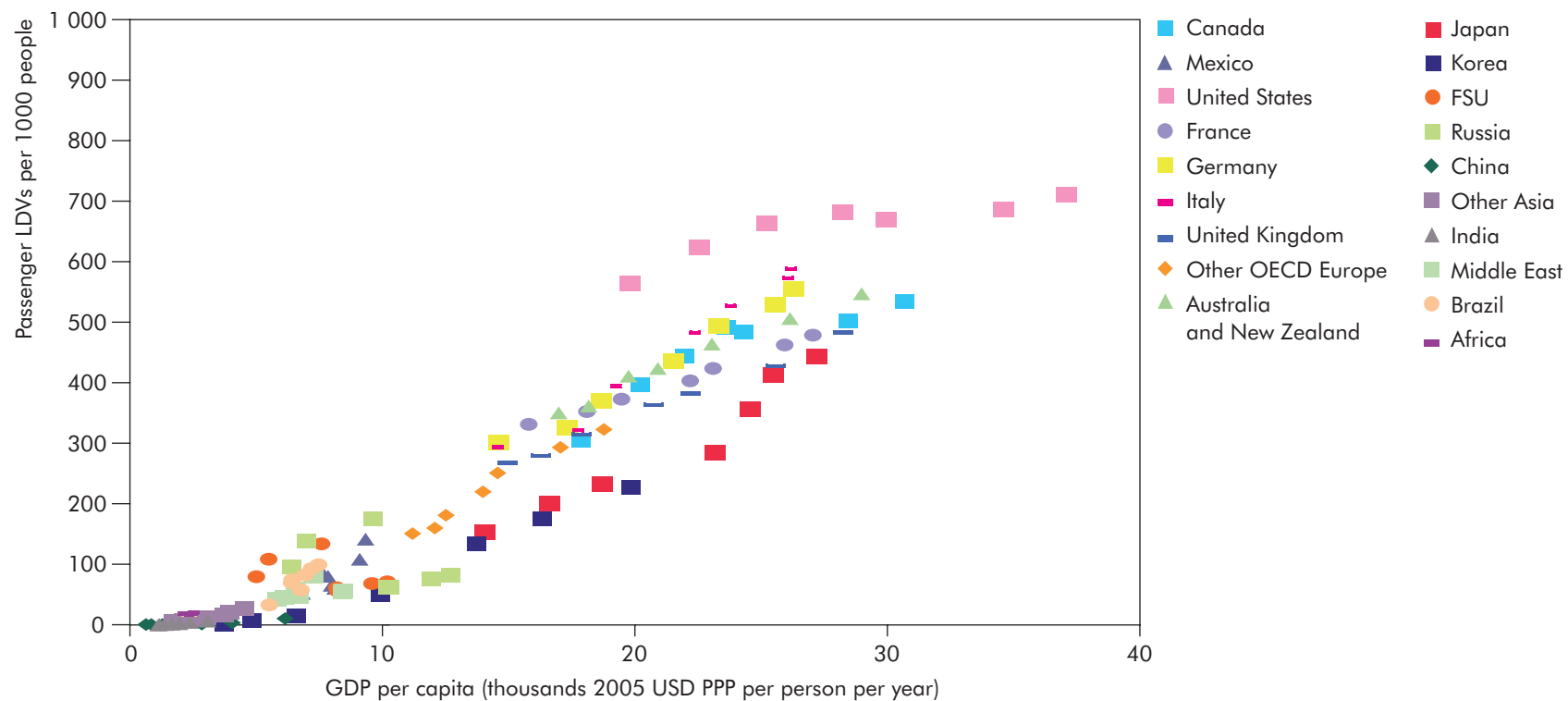
Passenger LDV ownership

Increasing incomes have enabled large numbers of people to acquire LDVs (Figure 3.5). Income and passenger LDV ownership are closely correlated worldwide although at a given level of per capita income some countries, such as the United States, have more than twice as many vehicles per capita as others.

Figure 3.5 also suggests a flattening of the rate of growth in LDV ownership as countries reach higher levels of income. It may be unlikely that many countries will reach ownership levels similar to those of the United States, *i.e.* about 700 passenger LDVs per 1 000 people, but they may well reach 400 to 600. While in the future about 10 billion people will live on the planet, this level of LDV ownership would mean 5 billion to 6 billion LDVs, or six to seven times more than the worldwide stock today. The IEA projections reach a little over 2 billion LDVs by 2050 in the Baseline scenario and about 3 billion in the High Baseline scenario, assuming that not all countries reach high levels of incomes in that time frame and that some developing countries will reach lower levels of LDV ownership than OECD countries at the same levels of income. But by 2100, there could be 5 billion vehicles on the roads if current trends were to continue unchecked for an entire century.

The numbers of LDVs in 2000 and 2005 in each country and region for which IEA has estimates are shown in Table 3.1. The table shows the wide variations both in LDV ownership rates and in sales/stock levels, and also how quickly sales are growing in some areas, especially China. Light-duty trucks (such as SUVs, mini-vans and pick-up trucks) are generally a low proportion of the total LDV stock in most

Figure 3.5 ▶ Passenger LDV ownership and personal income, 1970-2005



Source: IEA Mobility Model database.

Key point

Passenger LDV ownership rises steadily with average GDP per capita above USD 5 000.

countries, with the United States and Canada having the highest shares at around 50%. Light-duty trucks also hold a significant share in the Middle East, Korea, Japan and parts of Africa.

Table 3.1 ▶ Passenger LDV sales and stocks, 2000 and 2005

	Ownership rate (vehicles per 1000 population)		Stocks (millions)		Sales (millions)			Light truck (SUV, mini-van, pick-up) share of sales	
	2000	2005	2000	2005	2000	2005	Percent change	2000	2005
OECD North America	534	559	220	243	16.9	17.5	3%	36%	47%
Canada	501	535	15	17	1.4	1.3	-3%	38%	42%
Mexico	109	142	11	15	1.2	1.4	20%	12%	20%
United States	686	710	194	211	14.3	14.7	3%	39%	50%
OECD Europe	396	424	206	228	16.7	16.3	-2%	4%	6%
France	462	479	28	30	2.2	2.0	-6%	4%	6%
Germany	529	556	43	46	3.4	3.2	-6%	5%	7%
Italy	573	588	33	34	2.4	2.2	-6%	5%	7%
United Kingdom	427	483	25	29	2.3	2.5	8%	5%	9%
Other OECD Europe	293	323	77	88	6.4	6.3	-1%	3%	4%
OECD Pacific	367	404	72	81	6.6	7.0	6%	19%	23%
Australia and New Zealand	507	547	12	13	0.8	1.0	21%	14%	28%
Japan	413	444	52	57	4.7	5.0	6%	17%	19%
Korea	176	227	8	11	1.0	1.0	-5%	39%	33%
Former Soviet Union	108	134	24	29	1.5	2.0	32%	9%	13%
Eastern Europe	126	149	16	18	1.1	1.4	28%	1%	1%
China	4	11	5	14	0.7	3.1	319%	2%	5%
Other Asia	21	26	19	26	2.4	2.9	23%	20%	15%
India	4	6	4	7	0.6	1.1	73%	11%	26%
Middle East	59	80	10	15	1.3	1.6	24%	20%	30%
Latin America	74	78	31	35	2.6	3.1	18%	9%	15%
Africa	19	20	15	18	1.3	1.6	27%	13%	20%
Total (World)	103	111	622	714	51.7	57.6	11%	18%	23%

Notes: For non-OECD regions, data for many countries are estimated and are more reliable for some regions than others. Estimates for parts of Middle East, Other Asia, Other Latin America and Africa are particularly uncertain. Data issues are further described in the Appendix A.

Source: IEA Mobility Model database.

Table 3.2 ► Production of new passenger LDVs, and export destination, 2007

Country of production	Production (2007, thousand vehicles)	% Exported	Destination region (2007, thousand vehicles)							
			Asia	Middle East	North America	Central & South America	Africa	Oceania	Western Europe	Eastern Europe incl. FSU
Japan	9 945	58%	294	621	2 425	441	219	373	1 436	
China	6 381	6%		100						300
Germany	5 709	75%	407		623	29			2 640	476
United States	3 924	35%	25	165	766	45	19	45		306
Republic of Korea	3 723	73%								
France	2 551	77%	216		12	16			1 490	163
Brazil	2 388	25%	21		101	333	64			63
Spain	2 196	65%	12		33	6			1 446	154
India	1 708	13%								
United Kingdom	1 535	77%								
Canada	1 342	80%			900 (USA)					
Russia	1 289	-								
Mexico	1 209	79%			900 (USA)					
Czech Republic	926	94%								
Italy	911	41%								
Iran	882	-								
Belgium	790	77%								

Sources: IEA, based on OICA, JAMA, KAMA, ACEA, ANFAVEA, USITC.

■ no destination data/number too low

Passenger LDV production

Historically, the vast majority of LDVs have been produced and bought in OECD countries. In recent years, developing countries, especially Brazil, Russia, India and China, have developed their own manufacturing capacity in order to meet strong increases in demand. The recent appearance of low-cost LDVs may increase the tendency for locating LDV manufacturing facilities in countries with low labour costs.

Where the data are available and significant, Table 3.2 shows where LDVs were produced in 2007 and where they were exported to. The largest exporting regions, Europe, North America and South America, export to countries fairly nearby. China is now the second-largest LDV producer. Almost all Chinese production was consumed locally until the end of 2007, but Chinese exports to the Middle East, Russia and Africa have since started to grow rapidly.

3

Trade in second-hand vehicles

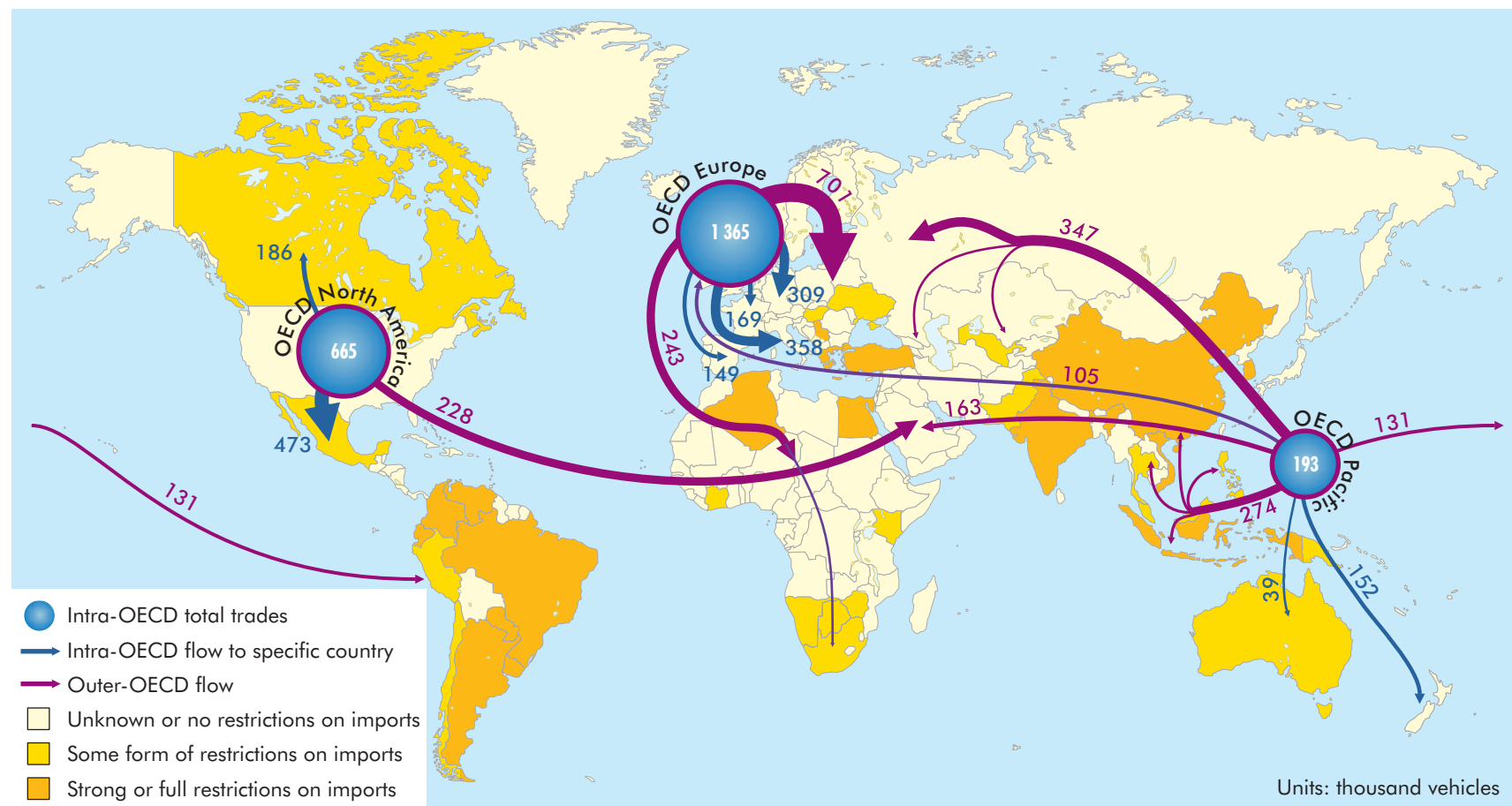
Some LDVs, after extensive use in one country, are exported to other countries for re-sale. Using the United Nations Commodity Trade Statistics Database (UN ComTrade), the National Institute of Advanced Industrial Science and Technology (AIST) in Japan has estimated that more than 5.5 million used LDVs were exported to another country in 2005. There are many uncertainties in these data. Second-hand imported vehicles are not always declared to customs offices, and different countries collect vehicle statistics in different ways. But the overall flow patterns show that OECD countries export about 90% of all internationally traded used vehicles (Figure 3.6). OECD North America and OECD Europe trade their used vehicles to a few, often close, regions. But OECD Pacific, and especially Japan, exports used vehicles all over the world, except where this is prevented from happening, e.g. through import restrictions; a number of countries restrict used LDV imports in this way, partly to prevent high emitting, unsafe or otherwise unsuitable older LDVs from being imported.

These estimates suggest that second-hand imported vehicles represent a significant share of newly registered vehicles in a number of regions (Figure 3.7), particularly in Eastern Europe and Africa.

Trends in travel per vehicle

Travel surveys and fuel use statistics indicate that LDV travel per capita is approaching saturation levels in most OECD countries and that the distances travelled by each vehicle each year may be declining, in part as the total number of vehicles on the road increases. For longer distance travel, faster modes such as air travel are growing faster than LDV travel. As ownership rates rise above one LDV for every two people on average in the OECD, and reach nearly 1.5 vehicles for every two people in the United States, more and more households own two or more vehicles. This leads to a flattening of, or even a decrease in, the average distance travelled by each vehicle each year (Table 3.3).

Figure 3.6 ▶ Used LDV flows around the world, 2005



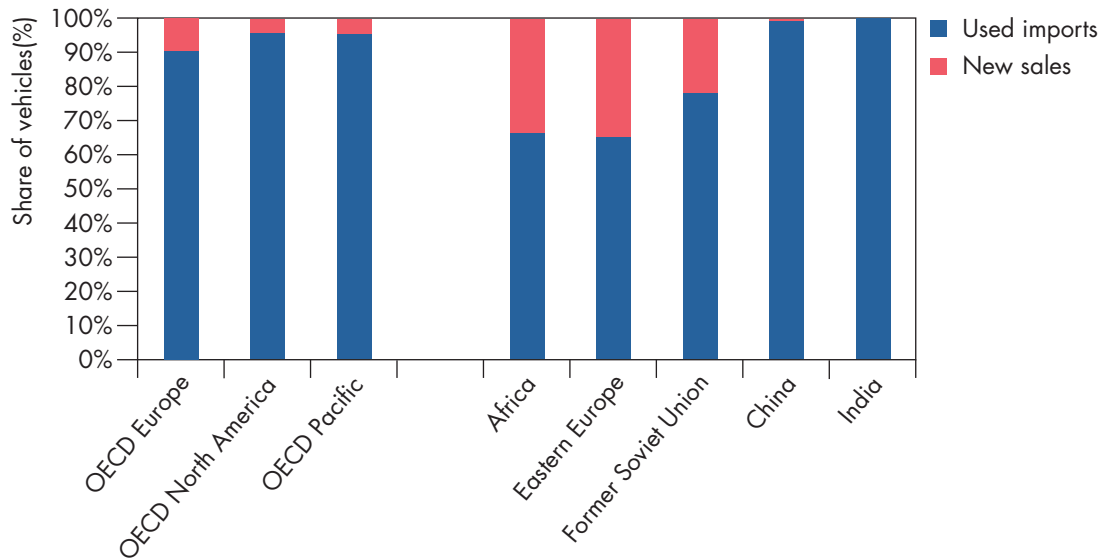
The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source: Fuse *et al.*, 2008.

Key point

A significant share of OECD LDVs has a second life in other parts of the world.

Figure 3.7 ▶ Proportion of used imports in total new registrations, selected regions, 2005



Source: IEA Mobility Model. Data are taken from available sources on a country-by-country basis and/or estimated.

Key point

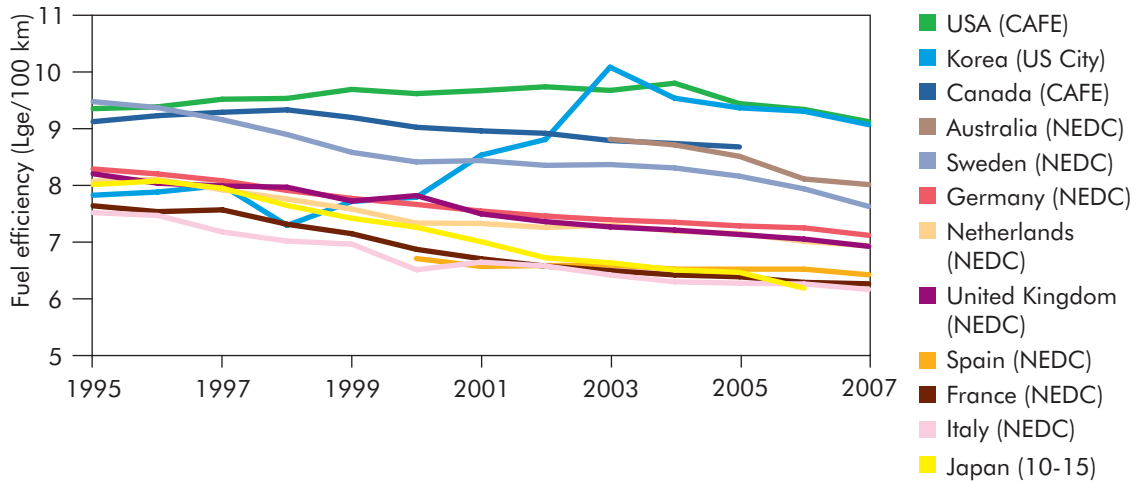
Used imported vehicles amount to over a quarter of “new” registrations in Africa and Eastern Europe.

Table 3.3 ▶ Average LDV travel (kilometres per vehicle per year)

Passenger LDVs	1975	1980	1985	1990	1995	2000	2005
United States	15 100	14 700	15 300	16 800	18 000	19 000	19 200
Canada			18 000	17 800	18 500	18 100	17 300
Japan				10 700	9 900	9 750	9 170
Australia and New Zealand			15 760	15 650	14 600	14 410	13 700
France				13 700	13 850	13 800	13 300
Germany				13 400	12 600	12 300	12 000
Italy				11 200	11 500	11 100	11 200
United Kingdom		13 800	14 200	16 100	15 900	15 100	13 700
OECD Europe				13 000	12 700	12 400	12 000

Source: IEA Mobility Model data based on various national travel surveys.

Few non-OECD countries report reliable data on travel per vehicle, so it is not possible to undertake a similar analysis beyond the OECD. One aim of the MoMo project is to obtain data or estimates of this type for each region, and eventually each country, in the world. Ideally, vehicle travel would be estimated on the basis

Figure 3.8 ▶ New LDV tested fuel economy in various OECD countries, 1995-2007

Notes: US City, CAFE, NEDC and 10-15 are acronyms referring to different test cycles that are not directly comparable.

Source: IEA Mobility Model database.

Key point

Steady improvements have occurred in many, but not all OECD countries since 1995.

of travel surveys. But few countries carry out such surveys on a sufficiently repetitive and consistent basis. Where no data are available, it is possible to estimate travel per vehicle using data on vehicle stocks, efficiency and fuel use. But for some countries, efficiency data and even stock data may not be reliable. Efforts to resolve such issues continue, as described in Appendix A.

Trends in vehicle fuel economy

Through much of the 1980s and 1990s, new LDV fuel economy, as tested, remained fairly constant across many OECD countries. It began to show steady improvements in Europe and Japan in the mid-to-late 1990s in response to new national and regional policies. This has increased the disparity in fuel economy between North American, European and Pacific OECD countries. In 2004, there was more than a 50% variation in the average fuel consumption rates for new LDVs across OECD member countries (Figure 3.8). Korea experienced a particular jump in average fuel consumption rates after 2000 due primarily to a rapid rise in SUV sales. A further comparison of LDV fuel economy and the various policies used to improve fuel economy in different countries is provided in Chapter 4.

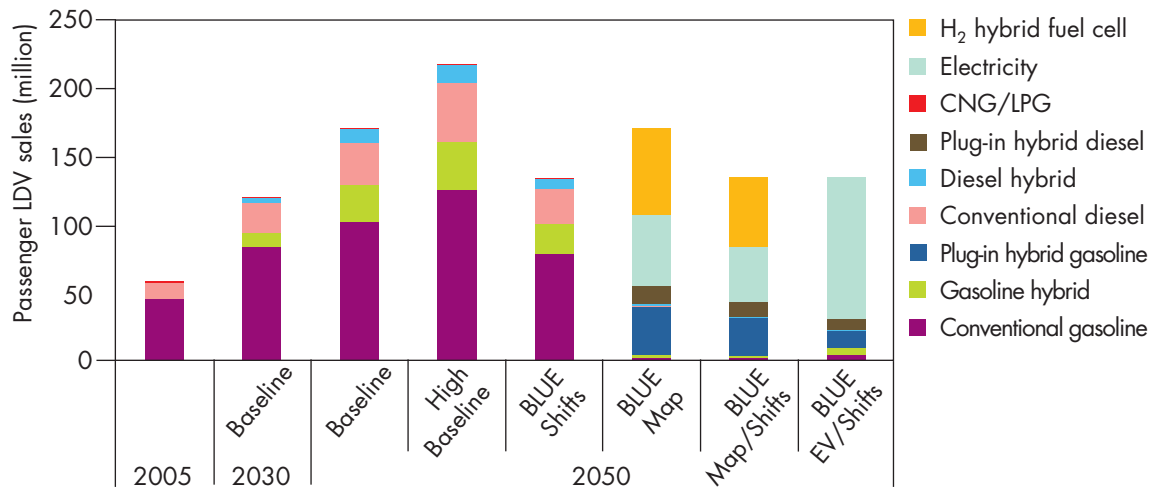
Projections and scenarios

Driven by income and population growth, in the Baseline scenario sales of LDVs around the world nearly triple to 150 million vehicles per year by 2050, from about 60 million per year in 2005 (Figure 3.9). The High Baseline scenario reflects even

higher ownership rates, with sales reaching 220 million in 2050. In the BLUE Shifts scenario, the shift from private to public transport constrains the growth in LDV sales to about 110 million in 2050, well below that in the Baseline scenario. Even this lower level of growth represents nearly a doubling of world vehicle sales from today's levels, as compared to the four-fold increase implicit in the High Baseline scenario. If underlying trends are closer to the High Baseline scenario than to the Baseline scenario, achieving the outcomes envisaged in the BLUE Shifts scenario would likely require especially strong policies around the world.

In addition, the types of vehicle sold vary considerably between scenarios. In the Baseline, High Baseline and BLUE Shifts scenarios, two-thirds of the new LDVs sold in 2050 are still conventional ICE vehicles, with the remaining third being hybrids. In the BLUE Map and BLUE EV scenarios, by 2050 over half of the vehicles sold are EVs or FCVs.

Figure 3.9 ▶ LDV sales by technology and scenario per annum



Note: BLUE EV/Shifts is a combination of BLUE EV success and BLUE Shifts.

Source: IEA Mobility Model.

Key point

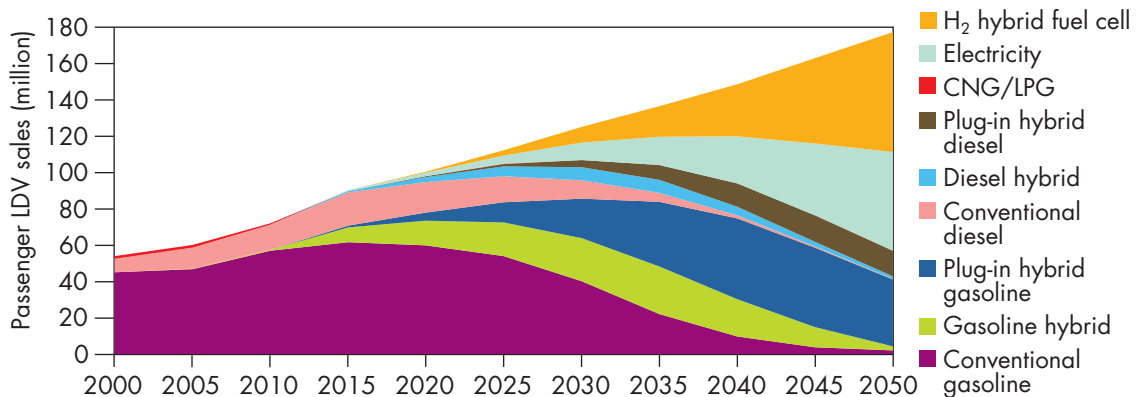
Nearly all LDV sales by 2050 in BLUE Map are PHEVs, EVs and FCVs.

In the BLUE Map scenario, changes over time are based on the projected evolution of technology potential and cost, described later in the chapter. Strong policies will be needed to bring about this scenario. As shown in Figure 3.10, after 2010 the rate of growth in conventional gasoline and diesel LDV sales begins to be trimmed by the sale of hybrids and PHEVs, with EV sales increasing after 2015. By 2020, PHEV sales reach 5 million and EV sales 2 million worldwide. Around 2020, commercial FCV sales begin. Through 2030, EV and FCV sales increase significantly, taking a progressively higher proportion of the overall growth in LDV sales. From 2030 onwards, demand for non-PHEV ICEs declines rapidly in absolute terms. By 2040,

more EVs and FCVs are sold than any ICE vehicle. By 2050, LDV sales are equally split between FCVs, EVs and PHEVs.

In the BLUE EV scenario, EVs and PHEVs dominate LDV sales by 2050. In the scenario, rapid cost reductions and performance improvements in batteries lead to the successful market introduction of EVs with substantial sales by 2020, which grow through to 2050. FCV growth could show a similar pattern, although at present it seems likely that EVs will grow more quickly, given the promising transition pathway offered by the existence of an electricity infrastructure and PHEVs as a transition vehicle.

Figure 3.10 ▶ Evolution of LDV sales by technology type in the BLUE Map scenario



Key point

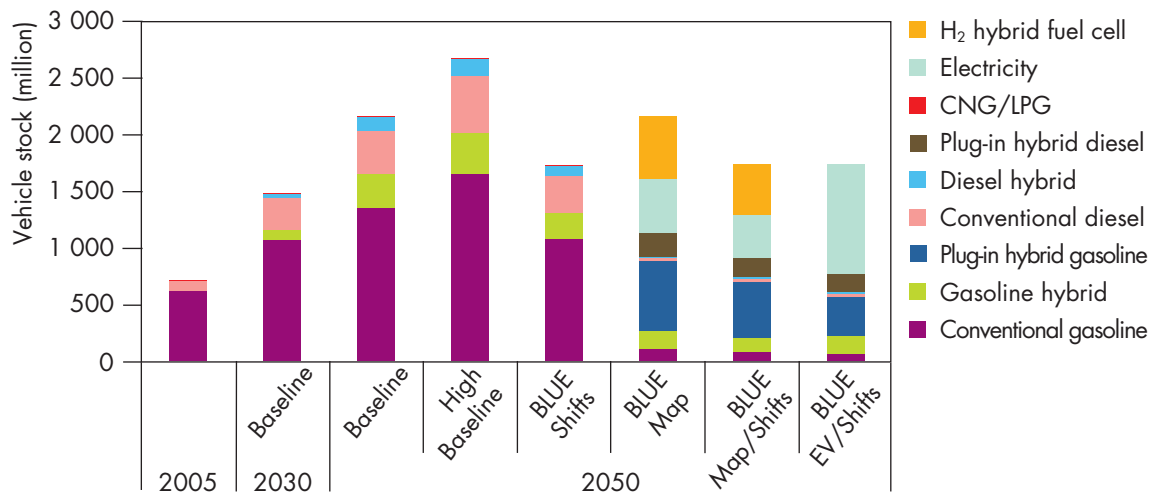
In BLUE Map, advanced technology vehicles such as PHEVs, EVs, and FCVs dominate sales after 2030.

Most LDVs stay in use for 15 to 20 years. Thus, changes in vehicle sales take time to affect the total stock of vehicles (Figure 3.11). In the BLUE Map scenario in 2050, for example, EVs and FCVs account for only about 45% of all LDVs on the road. It would take until 2065-70 for these vehicle types to represent the vast majority of all vehicles in use that is comparable to their share of sales in 2050.

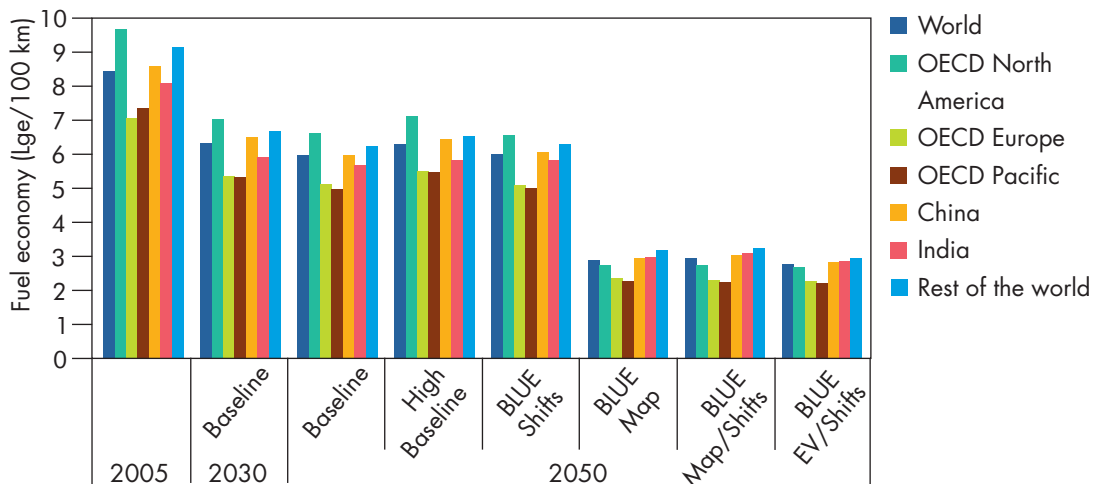
LDV fuel economy

Average LDV fuel economy is expected to improve over time. The rate of improvement is likely to be driven by technological improvements and their costs, by consumer choices regarding vehicle performances and size, by fuel costs and by policies to help achieve GHG targets. Not all these factors point in the same direction in all circumstances.

In the Baseline scenario, average new LDV tested fuel economy is expected to improve by about 25% by 2030 in both OECD and non-OECD countries (Figure 3.12). This is driven mainly by current (and, in some cases, very recent) efficiency policies in OECD countries such as the United States, EU Member States and Japan. Most of these policies are set to run through 2015. After 2015, if such policies are not renewed and strengthened, increases in vehicle

Figure 3.11 ▶ Vehicle stocks by technology and scenario**Key point**

In BLUE Map, vehicle stocks of EVs and FCVs are not quite 50% by 2050, but growing fast.

Figure 3.12 ▶ New LDV tested fuel economy for selected regions, 2005-2050**Key point**

LDV tested fuel economy improves dramatically in BLUE scenarios through 2050.

size, weight and power may start to reverse the benefits of higher efficiencies. The High Baseline scenario only reaches a net efficiency improvement of about 20% by 2030.

The improvements in non-OECD countries are expected to parallel broadly those in OECD countries. Eventually, more vehicles will be produced in non-OECD than in OECD countries. As this happens, it will be very important for non-OECD countries to have in place fuel economy policies that ensure efficiency technologies

are adopted and fully exploited, and that limit increases in average vehicle size, weight and power.

Beyond about 2020, electric motors and fuel cells will become increasingly important to support continuing improvements in LDV fuel economy. In the BLUE Map scenario, moving away from conventional gasoline and diesel vehicles toward PHEVs, EVs and FCVs improves new LDV fuel efficiency by a factor of two between 2030 and 2050 (Figure 3.12). While LDV fuel economy in OECD countries remains slightly better than in non-OECD countries, new LDVs in all regions use less than 3 Lge/100 km by 2050, compared to about 8 Lge/100 km today.

As discussed in Chapter 4, actual in-use fuel economy is generally worse than tested fuel economy, due to in-use conditions such as traffic congestion, use of auxiliary equipment, etc. The gap may exceed 25% in some countries, though appears to average about 15% to 20%. This gap could increase further in the future if, for example, traffic congestion worsens around the planet. Conversely, it could shrink with the introduction of better technologies, such as vehicle start-stop systems that stop the engine while a vehicle is at idle. Hybrids, PHEVs, EVs and FCVs all experience less deterioration in fuel economy in congested traffic than today's conventional ICEs. In the Baseline scenario, the gap between tested and in-use fuel economy for most regions remains around 15% to 20% in the future. In the BLUE scenarios, it improves to 10% by 2050 due to improved component efficiency, the introduction of advanced technology vehicles, and the use of policies to improve traffic flow and (in BLUE Shifts) cut the growth in car travel.

Energy use and CO₂ emissions

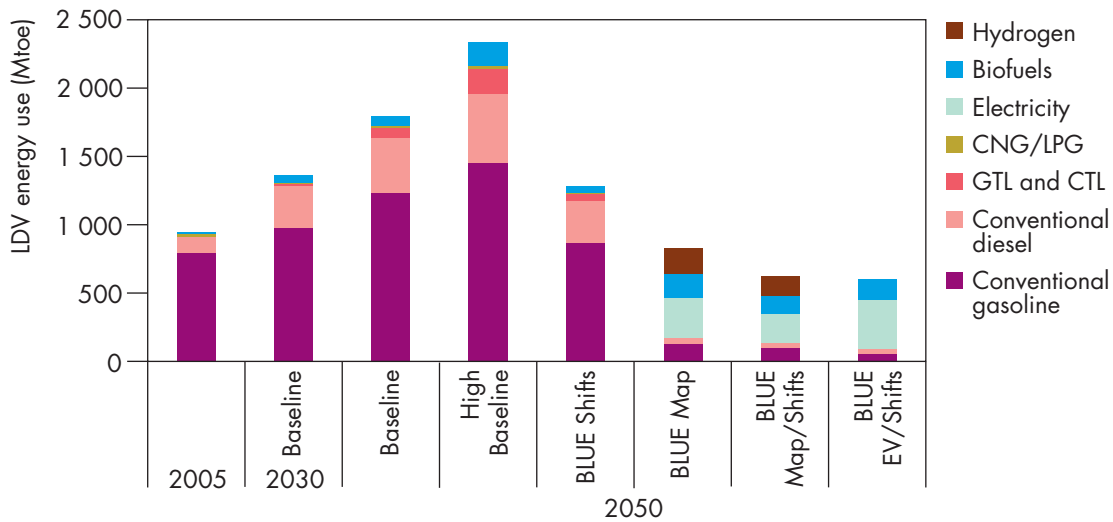
In the Baseline and High Baseline scenarios, the relative shares of different energy sources remain broadly constant as total energy use doubles or more by 2050 (Figure 3.13). In the BLUE scenarios, total energy use is far lower. In the BLUE Shifts scenario, with 25% lower car travel (as described in Chapter 5), the shares of different sources are very similar to those in the Baseline scenario. In the BLUE Map scenario, there is both strong fuel economy improvement and a major shift to biofuels, electricity and H₂ by 2050. Combining the BLUE Map and BLUE Shifts assumptions achieves a total fuel use of slightly more than half of the 2005 level. Combining the BLUE EV and BLUE Shifts assumptions results in electricity providing well over half of all LDV energy needs.

Changes in life-cycle, well-to-wheel GHG emissions from LDVs closely track the changes in petroleum energy use. In BLUE Map, GHG emissions reach an 80% reduction in 2050 compared to 2005 levels, and in BLUE Map/Shifts, nearly 90%. The role of different technologies in achieving this GHG reduction for BLUE Map is shown in the Executive Summary (Figure ES-2).

LDV technologies: current status



Although most current vehicles are gasoline or diesel powered, a wide range of propulsion and other vehicle technologies are available on the market. Some are

Figure 3.13 ▶ LDV energy use by scenario**Key point**

LDV energy use in 2050 in BLUE Map, Map/Shifts, and EV/Shifts is lower than 2005 and is dominated by low-GHG alternative fuels.

gaining in use or are poised to enter commercial markets in the coming decade. These include hybrids, in which electric motors or hydraulic pumps are combined with ICEs on the same vehicle, PHEVs and many other engine, drive-train and vehicle improvements that can improve efficiency or enable the use of alternative fuels.

Internal combustion engine (ICE) vehicles

Most ICEs use petroleum gasoline and diesel, but ICEs are suitable for a variety of different fuels. Spark ignition engines can work effectively, subject to minor modifications, using virtually all liquid and gaseous fuels including gasoline from refined petroleum, synthetic gasoline, LPG, methane or hydrogen, as well as alcohols such as ethanol and butanol. Compression ignition (diesel) vehicles can use diesel fuel, synthetic diesel and biodiesel. They can also, with relatively small modifications, use di-methyl ether (DME).

Engines

All engines have a point of optimum efficiency in terms of the power they deliver at a given speed of engine rotation. Real-life driving conditions, however, are highly variable. As a result, the loads imposed on engines match the designed optimal load only in a very limited range of situations such as uncongested, flat, highway driving at modest, steady speeds. Driving often makes demands that range far from the optimal load for the engine in question, for example during rapid acceleration. This causes a major drop in engine efficiency. Most technological development is aimed at enabling engines to operate more efficiently off peak, or

to increase the range of conditions in which they can achieve efficiencies closer to optimal performance.

Recent innovations in spark-ignition engines seek to apply modern compression-ignition approaches such as the direct injection of the fuel in the cylinder, alongside spark plug technologies, thereby raising the overall engine efficiency. Other approaches such as engine downsizing and turbocharging or the use of engine valves capable of adapting their timing according to different engine operating conditions, known as variable valve lift and timing, can also improve efficiencies. Advanced VVT systems could reduce or even eliminate the need for a throttle in spark-ignition engines, and could also be an enabling technology for the development of other advanced combustion technologies while limiting pollutant emissions (Rinolfi, 2006).

Additional fuel savings can be achieved by replacing the starter and the alternator with a single motor or generator, which allows the engine to be switched off when stationary in congested traffic conditions. Regenerative braking systems, as well as technologies that reduce engine friction or reduce the energy consumption of the ICE cooling circuit, can also lower fuel consumption (Smokers *et al.*, 2006).

Transmissions

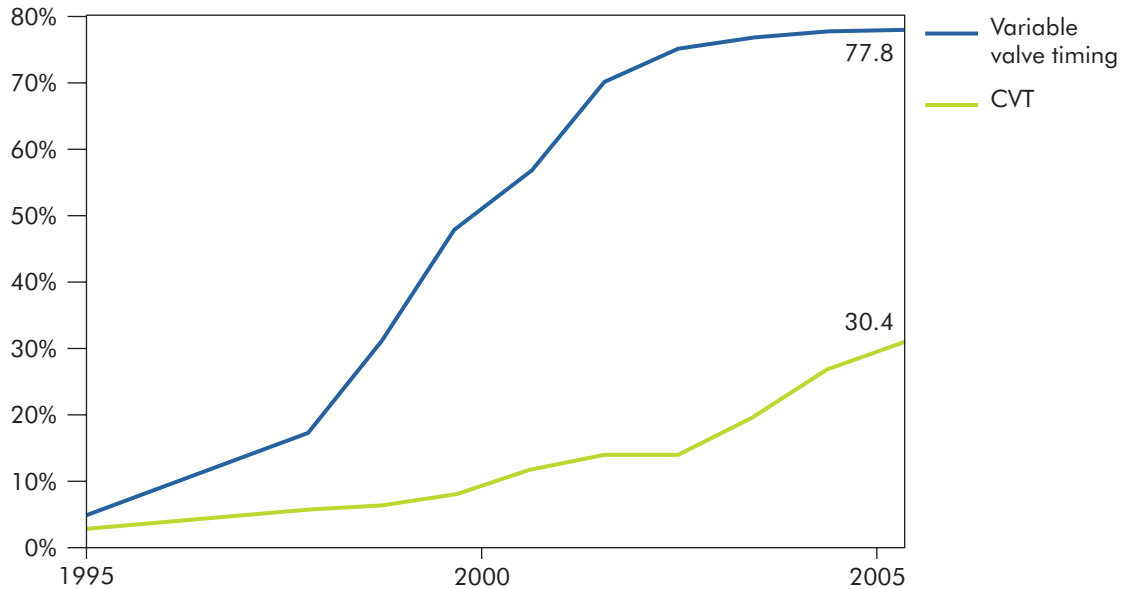
ICEs cannot directly deliver constant levels of power at different rotational speeds: they need transmission systems to convey the engine power to the wheels. This transmission involves energy losses, the significance of which depends on the transmission technologies in use. Most electrical motors do not need a transmission system, since they deliver levels of power much more closely related to their rotational speed.

Manual transmission requires a gearbox coupled with one or more clutches. It is about 97% efficient, since it does not rely on the use of fluids to switch from one gear to another. Automatic transmissions have efficiencies that are well below this level, at around 85%, given their need for torque converters to replace the clutch, which dissipates a significant amount of energy as heat. A new type of automatic transmission, automated manual transmission (AMT) which is particularly suitable for small vehicles, uses electronic controls to manipulate a conventional gearbox, with efficiencies that are comparable to those of conventional manual transmissions. Similar advantages are associated with dual clutch transmissions (particularly suitable for mid-size and large LDVs), also enabling a semi-automatic switch of gears while eliminating the need for torque converters.

Continuously variable transmission (CVT) systems do not need a gearbox. They work by exploiting a system of pulleys or toroidal transmissions connected by metal belts. They are not as efficient as manual transmissions, but can reach efficiencies of around 90% to 93% (Heath, 2007). CVTs are being increasingly used instead of conventional automatic transmissions (Figure 3.14).

CVTs and AMTs are likely to replace automatic transmissions entirely in the near future. AMTs could gain market share particularly in combination with dual clutch systems, which are more likely to be seen on medium and large vehicles.

Figure 3.14 ▶ Variable valve timing and continuously variable transmission in passenger LDVs in Japan



Source: JAMA, 2008.

Key point

For incremental technologies, market penetration can be quite rapid once introduction occurs.

Hybrid powertrains

Hybrid vehicles couple ICEs with another propulsion system.¹ Most current hybrids couple an ICE with an electric motor. Hydraulic hybrids are emerging as a possible option for commercial vehicles. In the longer run, turbines could eventually be coupled with ICEs or electrical systems.

There are three basic types of ICE-electric hybrid powertrain: serial, parallel and combined. In all cases, the electric motor is powered from a battery pack that is recharged by the ICE. In serial hybrids, the ICE is only used to charge the battery and the electricity stored in the battery is used to power the motor that drives the wheels. In this configuration, the ICE can be used at a nearly constant load most of the time, where its efficiency is best. In parallel hybrids, an ICE and one or more electric motors are able to deliver power to the wheels via the transmission. In combined hybrids, such as those used on the Toyota Prius, a power-splitting device is used to enable an ICE and one or more electrical motors to operate together depending on the driving conditions and the state of charge of the battery. The Prius has shown that the combined hybrid approach can be highly efficient.

Advances in electronics have been fundamental to the improvement of ICEs and the development of ICE-electric hybrids. Electronic devices are increasingly used

1. Sometimes the word “hybrid” is used to identify a vehicle capable of using two or more different fuels (e.g. gasoline and natural gas). This text treats such vehicles as multi-fuel vehicles, rather than hybrids.

to monitor parameters such as the temperature and pressure of the intake air, the quantity of oxygen in the exhaust, the status of the battery charge and the activity of many vehicle accessories. Electronic devices control the proper functioning of the engine, modifying the performance of components such as fuel injectors to maximise efficiency across the whole range of vehicle use. Most commercial ICE-electric hybrid vehicles for sale today are designed with drive-by-wire controls with no mechanical contact between the pedals and the engine. The further development of such electronic systems will constitute an essential component in the development of advanced powertrains.

ICE-hydraulic hybrids

ICE-hydraulic hybrids are emerging as a potentially promising technological solution particularly for heavier vehicles or for those with particularly high durability requirements. ICE-hydraulic hybrids combine an ICE with one or more hydraulic motors and pumps, and rely on a hydraulic energy storage system rather than a battery pack. The hydraulic system is mainly used to recover some of the energy deployed in braking by pumping hydraulic fluid into an accumulator.

In the parallel hybrid approach, the hydraulic pump is coupled through the transmission to the wheels. Under acceleration, the hydraulic energy in the accumulator is used to actuate the hydraulic pump to work as a motor to provide additional power to the drivetrain. In the serial configuration, the hydraulic pump directly turns the wheels while the ICE is used to provide pressure via the accumulator. The US EPA (2004) has tested and demonstrated the viability of LDVs equipped with hybrid hydraulic systems.

Pollutants and emissions control

Different types of engines emit different amounts of pollutants such as carbon monoxide (CO), volatile organic compounds (VOCs), hydrocarbons (HCs), nitrogen oxides (NO_x) and particulate matter (PM). Exhaust systems can reduce some of those emissions. Fuels may need to be adapted to enable the use of new engine and exhaust treatment technologies such as catalytic converters and particulate filters. Emissions regulatory systems throughout the OECD accordingly set emissions control requirements for vehicles in concert with fuel specifications for those vehicles.

Modern spark ignition engines with standard emissions control systems produce relatively low emissions of CO, hydrocarbons, NO_x and particulates, largely due to the use of three-way catalytic converters to treat the exhaust gases leaving the combustion chamber. Even so, to meet very tight NO_x emission regulations, spark ignition engines will require the use of NO_x traps.

Compression ignition (diesel) engines produce higher levels of NO_x and particulates than spark ignition ICEs. NO_x emissions can be reduced through the use of NO_x storage catalysts or selective catalytic reduction (SCR) systems.² Particulate filters can significantly limit particulate emissions.

2. NO_x storage catalysts store NO_x on a catalyst surface during the conventional operation of the engine and then reduce the oxides to nitrogen and oxygen during brief regeneration periods with particularly rich air/fuel mixes. SCR systems use reducing agents such as urea to convert NO_x back to nitrogen and oxygen.

Both NO_x absorbers and particulate filters increase the cost of vehicles. A particulate filter adds about USD 500 to the cost of a new vehicle (JRC, 2008a). NO_x traps could cost around USD 200 (Corning, 2007). Using particulate filters in LDVs also increases fuel use by around 2% (JRC, 2008a). Similar fuel economy penalties may be associated with NO_x absorbers because of the need for periodical regeneration. In the case of NO_x, however, the presence of after-treatment equipment in the exhaust would also allow marginal fuel savings that could compensate losses, since it would allow the ICE to work at higher temperatures. Additionally, the different after-treatment systems can be integrated, reducing the total cost.

Catalytic converters are only fully effective at temperatures of several hundreds of degrees centigrade. As a result, all ICEs emit more pollutants at cold start than they do after a certain time in operation. The incorporation of zeolites into the catalyst can help resolve this drawback. Alternatively, the catalytic converter can be heated before the engine starts, but this requires a battery that can store enough additional electricity for this function.

ICE hybrids typically produce fewer pollutant emissions than conventional ICEs, as their drivetrain is better tuned to changes in load and the engine is shut off during deceleration, idling and downhill driving. Hybrids still need catalytic converters and other pollutant emission control systems to contain the emissions of the ICE.

Advanced technologies and vehicles

Beyond today's emerging technologies, other technologies are under development that may help to make future vehicles even more efficient. Some involve new fuels such as electricity or hydrogen.

Plug-in hybrids (PHEVs)

PHEVs are essentially similar to conventional ICE-electric hybrids except that they also have the capacity to draw electricity from the grid to charge their batteries. They require electrical motors with sufficient power to drive the vehicle on their own in a wide range of driving conditions. They also require more battery capacity to increase the vehicle range on battery power and provide more motive power, since the vehicle is designed to run on the battery/motor system a significant percentage of the time.

PHEVs would rely mostly on their batteries in what is known as charge depleting mode, e.g. for commuting between home and work, after the batteries have been recharged at night or during working hours. ICE-electric PHEVs, however, can also function in the same way as conventional hybrids. When the battery is relatively low, for example on longer trips, the ICE can recharge the battery and work with the electric motor in a charge-sustaining mode. This characteristic adds a significant degree of flexibility in the design of PHEV, allowing manufacturers to choose amongst plug-in versions that have different degrees of reliance on the electric components for the delivery of power and energy. Different configurations can have very different range on electricity and system cost, especially for batteries.

The battery power in ICE-electric PHEVs may also be used when they are stationary either to offset electricity grid demands, for example in households, or to help

stabilise the electricity grid. Such uses would need to be supported by appropriate metering and billing systems. It is very unlikely that PHEVs will exist in sufficient numbers to play a part in grid stability in the near term.

Hydraulic hybrids could also work as plug-ins, using electricity or another energy source to run the pump that increases the pressure in the hydraulic reservoir. For such purposes, hydraulic reservoirs would need to be significantly scaled up or to withstand much higher pressures. Increasing working pressure is likely to result in increased conversion losses.

Electric vehicles (EVs)

EVs are entirely powered by batteries and a motor, without the need for an ICE. They are powered solely by electricity from the grid, which is stored in batteries or other storage devices on board the vehicle. They offer the prospect of zero vehicle emissions, as well as very low noise. An important advantage of EVs is the very high efficiency and relatively low cost of the electric motor. The main drawback is the need to rely exclusively on batteries, which are costly, heavy and cumbersome means of storing energy.

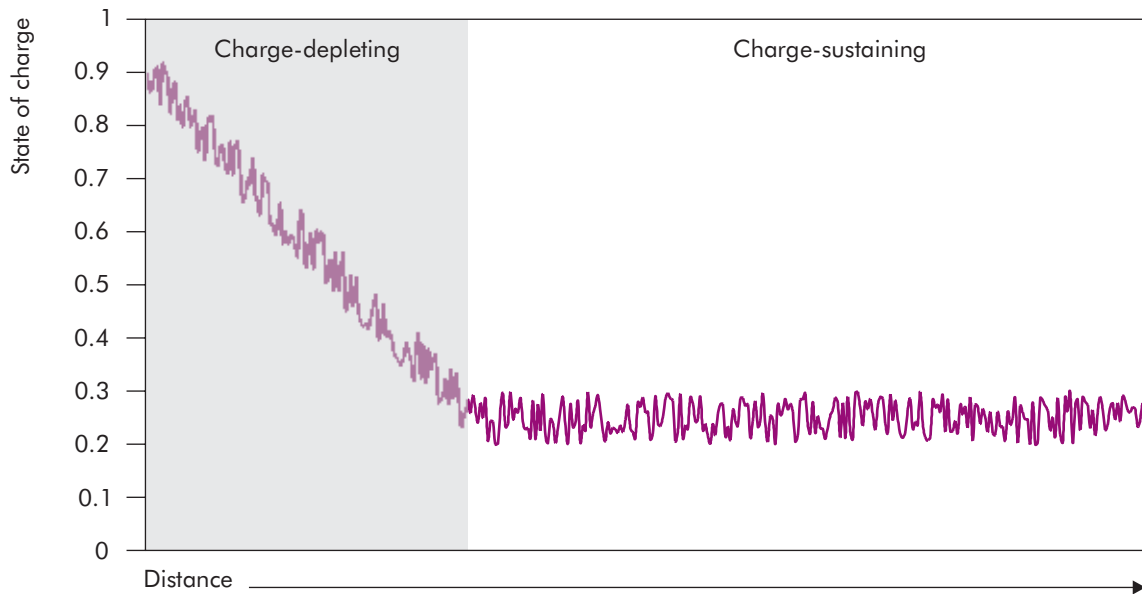
Given the high cost of batteries, their high weight and limited storage capacity, if EVs are to be cost-competitive, they need to compromise on their range. They may be particularly useful in towns and cities, where ranges are inherently shorter and where it may be easier and more cost-effective to set up recharging infrastructures. Viewing urban mobility as a service would enable conventional charging, fast charging and battery replacement to be integrated in such a way that EVs might be sold at prices that would exclude the relatively high capital cost of the battery. The battery cost would be recovered during its life as part of the cost of the electricity needed to run the vehicle.

Batteries for PHEVs and EVs

A number of technical issues, especially related to batteries, still need to be resolved. These may slow down the rapid and widespread introduction of EVs. Fast charging, for instance, may compromise battery life or may prejudice other battery characteristics, potentially increasing costs.

Batteries for PHEVs and EVs need to be designed to optimise their energy storage capacity. The need for higher specific energy and energy densities, as well as to contain costs, may lead to different technological choices than those that are appropriate for ICE-electric hybrids.

Batteries for PHEVs and EVs also need to be able to cope with a range of different discharging cycles. They will be subjected both to deep discharging cycles, for example on commuting trips, and to more frequent shallower cycles such as those from regenerative braking while driving. These demands are very different than those for batteries being used on conventional ICE-electric hybrids (Figure 3.15).

Figure 3.15 ▶ Deep discharge and charge sustaining modes**Key point**

Battery use for PHEVs typically includes a charge depleting followed by a charge sustaining mode. The latter is also the typical operating mode characterising batteries on HEV.

It seems likely that the first ICE-electric PHEVs will need to offer 30 km to 50 km of pure electric range. For this, they would need batteries with a storage capacity of roughly 6 kWh to 10 kWh, capable of delivering up to 75 kW or more if the vehicle is to run on battery-only power for some of the time.

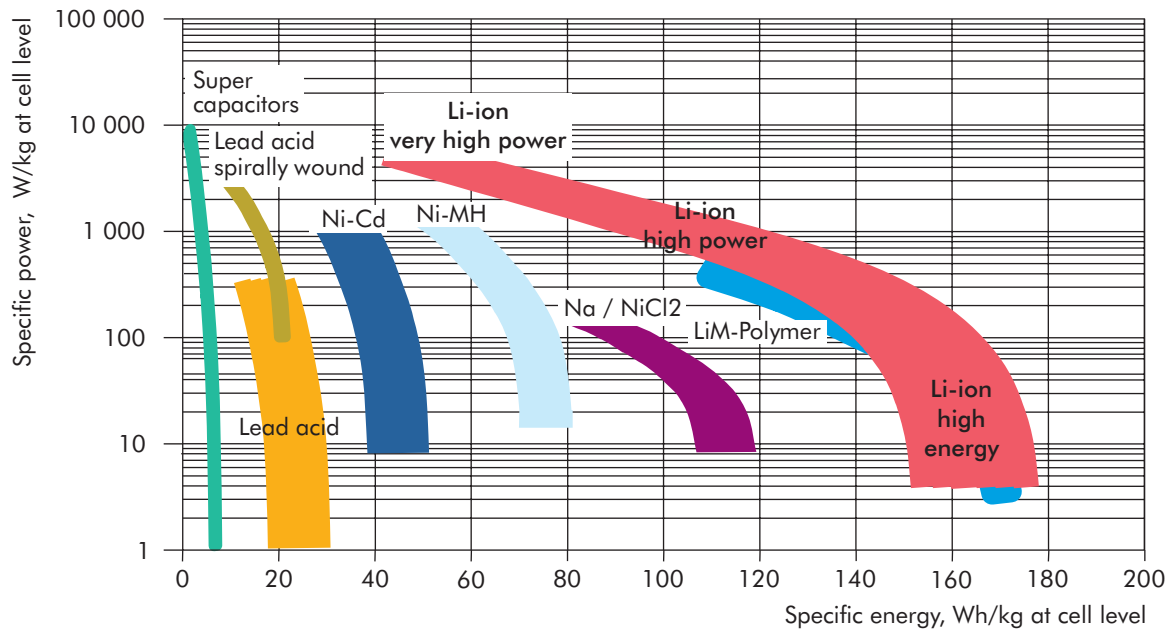
Figure 3.16 shows the specific power and specific energy of a number of technology options that could be used for batteries. The performance of many of these options is quite similar if they need to be optimised to deliver power. But lithium-ion (Li-ion) batteries appear to have an edge if there is a need to compromise between the capacity to store energy and the ability to release energy in a short time.

Fuel cell vehicles (FCVs)

FCVs use fuel cells to convert the chemical energy contained in hydrogen into electricity, which is used to power an electric motor that drives the wheels and support other vehicle functions.

Although several types of fuel cells have been developed, the most suitable for vehicle applications is the proton exchange membrane (PEM) fuel cell. They are relatively efficient, especially when partially loaded,³ and operate best at temperatures of around 80°C. As a result, PEM FCVs can start quickly, but they also need to be cooled to avoid overheating. PEM fuel cells use a solid polymer

3. Fuel cells are significantly more efficient than ICEs when operated at partial load in which circumstances they can achieve efficiencies of 50% to 60%. At high loads, the efficiency of the two systems is similar at around 35% to 40%.

Figure 3.16 ▶ Specific energy and specific power of different battery types

Sources: Andrew, 2006; Rosenkranz, 2007.

Key point

Li-ion batteries can be configured to provide far higher specific energy and specific power than most other commercial battery types.

as an electrolyte and porous carbon electrodes with a platinum catalyst. The use of platinum makes PEM cells highly sensitive to carbon monoxide and sulphur pollutants. As a result, they need to be fuelled by very pure hydrogen. Hydrogen produced from natural gas, for instance, is likely to require purification before being used by PEM fuel cells.

FCVs are well suited to recover the energy dissipated in braking, since their motors can be reversed to act as generators. This, together with the fact that fuel cells achieve their maximum efficiency at partial loads, suggests that they are particularly well adapted to use in hybridised electric vehicles in which the batteries can be used both to store recovered braking energy and to help provide peak power. Hybridisation in this way can also help reduce costs if the battery has higher specific power and lower cost than the fuel cell stack, as seems likely to be the case when comparing Li-ion battery costs to fuel cell system costs. Given these considerations, it seems most likely that FCVs will at least initially be FCV-EV hybrids⁴ (Ahluwalia *et al.*, 2005).

The refuelling of FCVs raises difficult issues. They either need on-board reforming, which is expensive and requires production of very pure H₂, or they need on-board H₂ storage, which will need to be supported by an extensive H₂ production and distribution infrastructure. As fuel cell systems improve and FCVs are proven technically, the refuelling and fuel infrastructure issues are likely to become the main

4. FCVs could even be conceived as plug-ins, if they have sufficient storage capacity and their batteries are optimised for such a configuration.

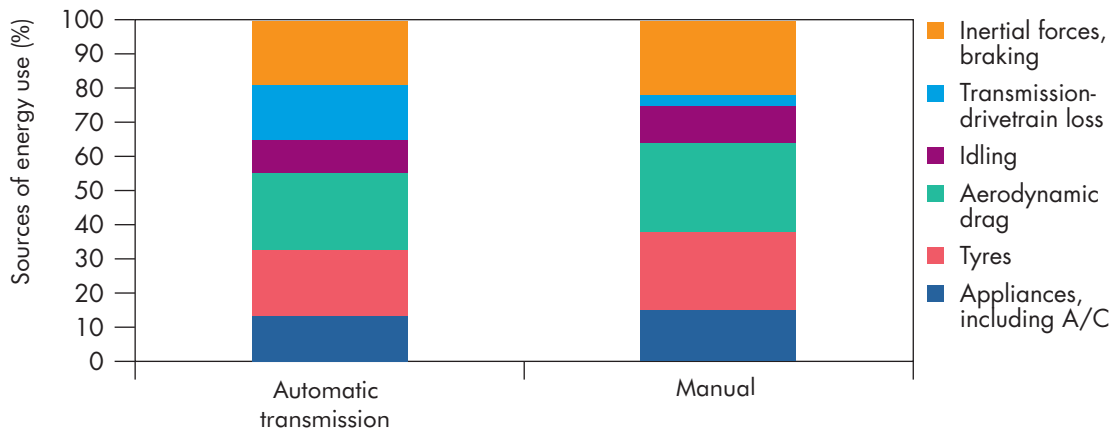
barriers to commercialisation. Fuel cell system costs have declined (as discussed below), but are still very expensive compared to conventional ICE vehicles.

Non-engine technologies

Excluding efficiency losses in the powertrain, aerodynamic drag accounts for about 25% of the total energy used by a vehicle in mixed urban and highway driving, and for about 40% to 45% when a vehicle is driven at typical motorway speeds (Figure 3.17). The remaining energy is dissipated in the tyres, in powering lights and auxiliary equipment, in powering air-conditioning systems, while idling, and in the transmission system. The balance of around 25% to 30% in mixed driving or 10% in highway driving is used to overcome inertial forces and then lost in braking.

3

Figure 3.17 ▶ Energy use in a spark-ignition powered vehicle, excluding thermodynamic losses in the powertrain



Sources: IEA elaboration based on Duleep, 2005 and TRB, 2006.

Key point

The energy requirement on vehicles is unevenly dissipated through aerodynamic drag, braking, heat loss in the tyres, the energy demand for electric appliances (including lighting), idling and transmission losses. Transmission-drivetrain losses are far higher for automatic than manual transmissions.

A set of technologies can target the energy consumption associated with each of these components, reducing the final power requirements of the vehicle while leaving its performance unchanged. These technologies include:

- Improved aerodynamic designs.
- Low rolling-resistance tyres and tyre inflation indicators.
- More efficient lighting.
- More efficient auxiliary systems and air conditioning.
- Increased use of lightweight materials.

Improved aerodynamics

Efficiency losses due to aerodynamic drag are proportional to the front surface of the vehicle, the square of the vehicle speed and a factor that depends on the aerodynamic profile of the vehicle (the drag coefficient, C_x).

Modern LDVs have a typical drag coefficient of between 0.3 and 0.35.⁵ Some models, such as the Toyota Prius, have been designed to minimise drag, achieving coefficients of 0.26 or even lower. Others, for example some SUVs, are characterised by C_x values that are well above 0.35. A 15% reduction in drag coefficient (e.g. from 0.32 to 0.275) can reduce drag-related energy losses by around 3%. But, given that lower drag can also enable lower power and torque requirements for the same vehicle performance, the total potential fuel economy improvement associated with 15% lower drag could amount to 3% of the total energy consumption of the vehicle.

Low rolling-resistance tyres and tyre pressure monitoring

Low rolling-resistance (LRR) tyres are widely used during vehicle tests and when vehicles are sold. But they are rarely purchased as replacement tyres due to their high initial cost, the lack of clear information for consumers, and limited market availability. In the European Union, the worst tyres on the market have twice the RR of the best. Some modern tyres have an RR up to 30% lower than the best tyres produced in the early 1980s.

If all LDVs were to use LRR tyres, it is estimated that efficiency improvements of 20% to 25% over today's average tyres could be achieved. Since roughly 15% to 20% of the energy delivered to the transmission is lost as heat in the tyres, the total efficiency improvement that might be available is of the order of 3% to 4% (Penant, 2005).

In most real-world driving conditions, tyres are underinflated compared to their optimum performance level. Installing tyre pressure monitoring systems with dashboard inflation indicators could be expected to improve tyre maintenance and to lead to an improvement in the range of 1% to 2% in overall non-powertrain vehicle efficiency (Penant, 2005; Stock, 2005).

Energy efficient lights

On average, about 2% to 3% of vehicle fuel is currently used to provide lighting (IEA, 2006). Around 60% to 70% of this energy is used for headlights, which consume about 1.5% of the fuel of a vehicle when they are switched on. Fuel consumption attributable to lighting is higher in locations where regulations require the operation of daytime running lights or of lights that are permanently set to be on, such as in Canada and the Nordic countries.

Headlights relied on incandescent lamps for decades, before switching almost completely to halogen lamps within the past ten years. Halogen lamps are about 60% more efficient for a given luminosity. Halogen lamps have begun to give way

5. This number, the drag coefficient, is higher for bodies that have a rather blocky shape, and lower for those that have a streamlined aerodynamic shape.

to xenon lights, first introduced in Europe in 1991, especially in expensive vehicles. Xenon lamps are up to four times more efficient than halogen lamps, but in existing applications they are often used to provide additional light rather than primarily to reduce energy consumption. Xenon lights could deliver a 2% overall energy saving if they were used to provide the same luminosity as halogen headlight lamps, and a 1% saving if they were used to double the luminosity achieved with halogen lamps.

Light emitting diodes (LEDs) have increasingly been used to replace incandescent lamps for vehicle braking lights. LEDs are highly visible, have a long lifetime, activate instantly and are very compact. LEDs are 40% to 80% more efficient than halogen lamps.

Innovative solutions based on white LEDs are also starting to emerge. White LED lights offer space savings, better styling options, a good chromaticity and low maintenance costs. They may become particularly suitable for daylight running applications. Currently, though, the technology has not matured enough to be considered for headlights, and costs are still higher than xenon lamps.

Improved air-conditioning systems

Mobile air-conditioning (MAC) systems began to be introduced in the United States in the early 1960s and in Japan in the 1970s. The numbers and percentages of air-conditioned LDVs in Europe and in developing countries only started to increase during the 1990s (Clodic *et al.*, 2005). In 2000, nearly half of the worldwide automotive fleet was equipped with MAC, and a significantly larger share of new vehicles, probably above 80%, is currently being sold with a MAC system fitted. This share continues to grow and may eventually approach 90% to 100% in most countries, if recent trends continue.

MAC systems use a refrigeration cycle to reduce the temperature of the vehicle interior. Since the recognition in the early 1990s of the need to reduce the emission of ozone depleting substances, all LDV manufacturers in developed countries have used HFC-134a (a powerful GHG) as the refrigerant fluid. Increasing concerns about GHG emissions have led the European Commission to propose the phase-out of HFC-134a. Two main options are under consideration to reduce GHG emissions from MAC systems: improving the current HFC-134a system by reducing leakages, or switching to refrigerants with a lower global warming potential such as CO₂ or HFC-152a.

Using MAC systems with external temperatures in the range of 28°C to 35°C at a relative humidity of 50% to 60% can double fuel consumption in small or efficient vehicles (Malvicino *et al.*, 2009). It has been estimated that MAC systems operate for about 24% of the annual vehicle running time in a city located in continental Europe (Paris), 60% in southern Spain (Sevilla) (Clodic, 2005) and over 60% in cities with very hot and humid conditions throughout year. In the conditions typical of continental Europe, the average annual fuel consumption attributed to MACs has been estimated to be around 6% to 7%. This increases to approximately 15% in hotter climates such as those found in southern Spain. In tropical countries, this percentage can be expected to be higher still.

Many MAC systems currently in use, especially in North America, rely on a belt-driven, fixed displacement compressors and manual controls. Such systems are designed to produce a large cooling capacity and to regulate temperatures by warming any excessively chilled air. They waste significant amounts of energy compared to more advanced systems. Since the mid-1990s, variable capacity technology has been introduced mainly in Europe and Japan. This avoids excess cooling and reduces energy consumption.

Further improvements in efficiency can be delivered by the use of electricity-driven compressors (particularly on ICE-electric hybrid vehicles) and improved compressor controls. The use of an external control compressor (*i.e.* a compressor in which the refrigerant flow is externally controlled according to the cooling needs of the vehicle), in particular, yields significant efficiency gains in the range of 25% to 35%, even if the mechanical efficiencies of external control compressors are in the same range as internal control compressors (Benouali *et al.*, 2003). A switch to CO₂-based systems would not affect significantly this potential gain.⁶

The introduction of new propulsion systems is likely to affect the design of MAC systems. High-efficiency engines may not produce enough heat in cold temperatures and therefore require an additional heating system. Heat pumps, which are being developed alongside conventional heating options, may be useful in this context. Stop-start and hybridised engines also may affect the development of MAC systems, since stopping the engine will put a heavy strain on the batteries unless separate storage systems or electrically driven (or hybrid⁷) compressors are introduced. EVs would require significant changes in MAC systems. Electrically driven, reversible heat pumps may be the best option in this context.

Better insulation, reducing window sizes, and using glass designed to maximise the reflection of the solar heat can all also help to reduce the final energy consumption of MACs. Improvements in the evaporator and condenser design can also result in better airflow management and energy efficiency.

Taking all these options together, it is estimated that improved MACs could deliver a 3% to 4% efficiency saving in total vehicle fuel consumption in climate conditions averaging those found in continental Europe and Southern Spain, with the former region weighted twice as much as the latter. The saving would be much higher in hotter and more humid places (such as tropical countries), and lower in colder places (such as the Nordic countries).

Material substitution

Vehicle inertia (the tendency to remain at rest or remain in movement) results in significant energy losses. Inertia can be reduced by decreasing the vehicle's weight, with the potential to achieve significant energy savings. Vehicles can either be made smaller, or they can be made lighter through materials substitution or better design. Vehicle weight reductions both reduce inertial energy losses and enable lower engine sizes and power requirements, which result in additional fuel and cost savings.

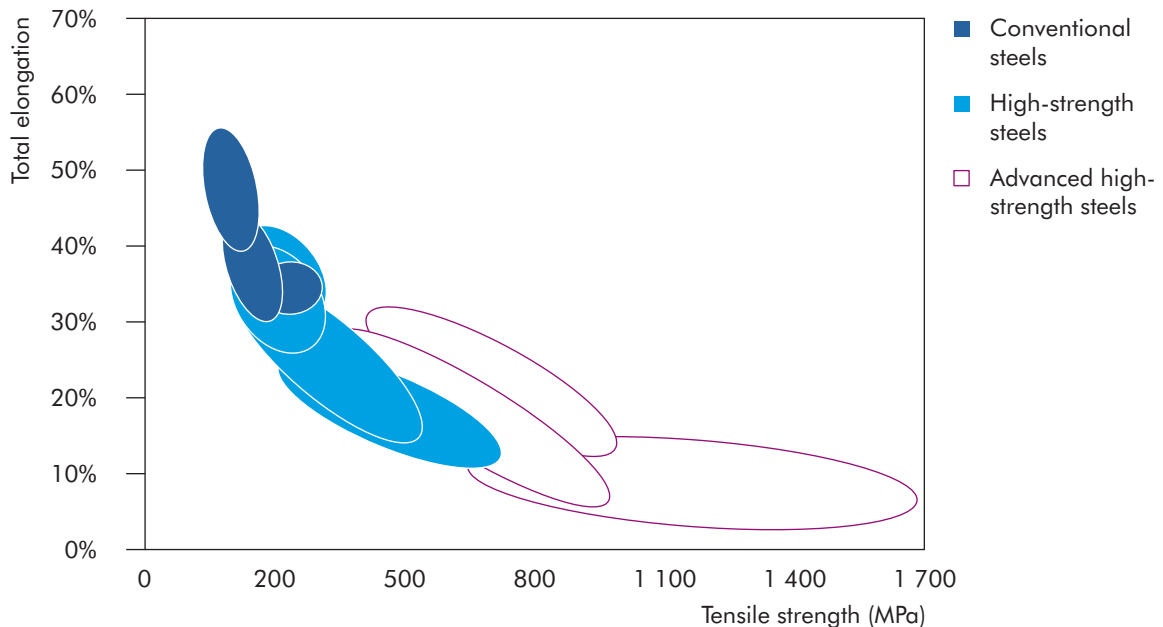
6. A recent study funded by the European Union showed that CO₂-based MAC systems can achieve the same efficiency level as externally controlled HFC-134a systems.

7. A hybrid compressor can be driven by the engine belt while the engine is running and by the electric motor during engine stop.

Material substitution encompasses a number of possible solutions, including the more extensive use of high-strength steels (HSS) and advanced high-strength steels (AHSS), aluminium, magnesium, plastics and composites. Radical material substitution solutions are sometimes associated with more radical changes in design and construction techniques.

HSS is stronger per unit weight than conventional steel (Figure 3.18) and can enable vehicle weight reductions. But its higher strength also makes it more difficult to work in the manufacturing process, leading to higher maintenance costs for the factory equipment. The use of HSS has increased significantly over the past 15 years (JRC, 2008b; Federici *et al.*, 2005), largely driven by increased demand for safer vehicles particularly in Europe. HSS is likely to comprise more than 50% of the total steel weight of several vehicle models.

Figure 3.18 ▶ Characteristics of different types of steel



Source: FKA, 2006.

Key point

High-strength steel is stronger per unit weight than conventional steel and can enable vehicle weight reductions. However, its higher strength also makes it more difficult to work with in the manufacturing process.

Aluminium can be used to replace both steel and cast iron in several vehicle components, thereby delivering important weight savings. It is best suited to being used for castings that replace cast iron for several powertrain components such as the engine block, cylinder heads, transmission housing and intake manifold. Magnesium alloys are also suitable for some of these applications, delivering even larger weight savings than aluminium.

Aluminium can also be used for sheet and forgings, typically in body parts and in the suspension, drive-shaft and wheel rims. Aluminium sheets and forgings are significantly more expensive and rather more difficult to integrate into a

conventional vehicle frame than HSS components. Without significant changes in the way vehicles are designed, aluminium is unlikely to be widely used to reduce vehicle weight.

The life-cycle GHG emissions attributable to HSS are lower than those attributable to aluminium, particularly as a result of the lower GHG emissions involved in HSS production.

Plastics started to be used more widely on vehicles in the late 1970s, mainly to replace non-structural features and for interior components. Polymer composites have not made much inroad into wider applications, mainly because of issues related to manufacturability and in particular the lack of a manufacturing method that is suitable to the automotive production environment of tens or hundreds of thousands of units per year.

LDV fuel economy potential and cost analysis

This section provides estimates of technology cost and fuel savings potential for the range of technologies discussed above, based on data and information provided by many recent studies.⁸

Gasoline and diesel engines

The efficiency of both spark ignition gasoline and compression ignition diesel engines is expected to continue to improve, albeit at a cost (Table 3.4). The IEA estimates that an improvement of 24% in the fuel economy of LDVs, compared to the average performance in 2000-05, can be achieved with technologies available today, increasing only slightly over time, to 28% in the longer term. The emergence of other technologies could, of course, change this picture in the future.

The costs associated with the achievement of a 24% to 28% improvement in the efficiency of spark ignition engines appear likely to be around USD 2 200 per vehicle. A potential 30% to 33% improvement in the efficiency of compression ignition engines appears to be achievable at a cost of around USD 3 200 per vehicle. These figures take into account interactions between technologies. They also include the fuel economy and cost penalties associated with systems aimed at reducing pollutant emissions. The figures exclude (as in all the following cases presented) the fuel savings that each technological contribution generates, as well as the mark-up expected from manufacturers once they introduce new technologies to the market.⁹

8. In most cases, the sources for individual estimates are not cited in the text, but a range of studies was used to develop the IEA estimates. These include: Ahluwalia *et al.*, 2005 and 2008; Andrew, 2005; Benouali *et al.*, 2003; Calwell, 2005; Camano Associates, 2005; Carlson *et al.*, 2005; Clodic, 2005; Clodic *et al.*, 2005; Duleep, 2005; ECMT/IEA, 2005; EPA, 2004; FKA, 2006; Fleet *et al.*, 2008; FUIRORE, 2003; IEA, 2006; Jackson, 2007; Johnson, 2007; JRC, 2008; Kasseris and Heywood, 2006; Kromer and Heywood, 2007; NESCCAF, 2004; Olszewski, 2007 and 2008; OTA, 1995; Penant, 2005; Rinolfi, 2006; Rosenkranz, 2005; Smokers *et al.*, 2006; Smokers, 2008; TRB, 2006; Stock, 2005; Tatsumi, 2007; Van den Bossche *et al.*, 2005; and Yang *et al.*, 2008.

9. A high-volume markup of about 10% is assumed here. The actual value of this factor can vary significantly and depends on several parameters such as the volume expected to be produced and vehicle market class.

Table 3.4 ▶ **Estimated improvement potential and costs relative to a spark ignition engine, 2005**

	Improvement potential (% of reduction in fuel use, cumulative)		Cost (USD/vehicle, cumulative)	
	Near term	Long term	Near term	Long term
Spark ignition engines				
Emission control requirements	-1%	-2%	250	350
Reduced engine friction	0%	0%	310	350
Starter-alternator	7%	7%	560	480
Variable valve lift and timing (VVT)	12%	11%	800	710
Advanced cooling circuit + electric water pump	14%	13%	950	840
GDI stoichiometric, including downsizing and turbocharging	20%	19%	1 570	1 060
GDI advanced (CAI, with VVT)		23%		1 580
Transmission improvements	24%	28%	2 200	2 150
Compression ignition engines				
Emission control requirements	-3%	-4%	500	700
Reduced engine friction	-1%	-2%	560	700
Starter-alternator	6%	4%	880	890
Diesel engine	24%	22%	2 440	1 960
Advanced combustion in diesel engines		26%		2 480
Advanced cooling circuit + electric water pump	26%	28%	2 590	2 600
Transmission improvements	30%	33%	3 220	3 160

Technology costs should drop over time via technology learning and optimisation as technologies gain market share and as cumulative production increases. But much is already known about spark ignition ICEs and transmission technologies, so the overall cost-reduction potential in these areas may be limited. The potential for efficiency improvements in compression ignition diesel engines is higher. Even after allowing for the fuel costs of additional NO_x emission restrictions, diesel engines have the potential to show a longer-term fuel efficiency improvement of around 33%.

Intermediate solutions delivering less than the full technology potential at lower cost (and still providing fuel savings) help to ease the market introduction of these and other technologies.

Hybrids

ICE-electric hybrid vehicles consume less fuel than conventional ICE-powered vehicles because the electric motor replaces the use of the ICE in conditions where it is performing particularly inefficiently. Additional energy savings come from recovering energy during braking and shutting the engine off in congested traffic conditions to minimise idling. Hybrids also have lower transmission losses. These fuel economy improvements are partially offset by additional weights, mainly due to battery packs and devices such as the electric motor-generator. The estimated fuel economy potentials and costs for spark ignition (gasoline) and compression ignition (diesel) hybrids are shown in Table 3.5.

Table 3.5 ► **Costs and improvement potentials for ICE-electric hybrids relative to a spark ignition engine in 2000-2005**

	Improvement potential (% reduction in fuel use, cumulative)		Cost (USD/vehicle, cumulative)	
	Near term	Long term	Near term	Long term
Spark ignition ICE-electric hybrid powertrain				
Emission control	-1%	-1%	180	230
Atkinson cycle	3%	2%	220	270
Reduced engine friction	4%	4%	290	270
Hybrid system	37%	36%	2 630	1 750
Advanced cooling circuit + electric water pump	39%	38%	2 750	1 850
Gasoline engine, GDI stoichiometric	39%	43%	2 750	2 410
Gasoline engine, VVT or GDI stoichiometric	41%	45%	2 980	2 640
Compression ignition ICE-electric hybrid powertrain				
Emission control	-2%	-2%	380	490
Reduced engine friction	-1%	-1%	440	490
Advanced cooling circuit + electric water pump	1%	1%	560	590
Hybrid system	29%	30%	2 910	2 070
Advanced diesel engine	42%	41%	4 470	3 260

A typical spark ignition, gasoline-powered hybrid commercially available today delivers fuel efficiency improvements of around 30% compared to a conventional spark ignition ICE on a mixed urban/highway drive cycle. The improvement is larger in the case of urban-only or congested driving, since it is in these situations that conventional ICEs are most inefficient, whereas hybrids can run on their electrical motors, recover energy while braking and eliminate idling losses.

The cost associated with the fuel economy improvement delivered by hybrids is primarily attributable to the cost of the battery pack, with additional costs coming

from the need for an electric motor and generator, and an improved transmission system. Typically, current ICE-electric hybrids use batteries with relatively low energy storage capacity but high power responses. Such batteries are generally maintained at a fairly constant state of charge around 50% of the full charge. They are usually able to store about 1.2 kWh of energy and cost around USD 650/kWh. Virtually all hybrid batteries today are nickel-metal hydride (NiMH), but these will likely be replaced with Li-ion batteries as these become available for EVs in the near future.

The resulting estimate for the incremental cost of a spark ignition ICE-electric hybrid, over and above the ICE technology currently in use, is around USD 2 450 per vehicle — excluding development costs for the components and costs associated with the extensive changes in vehicle required for ICE-electric hybrids. This may decrease to about USD 1 600 once battery costs decline.

Commercially available ICE-electric hybrids do not yet exploit the full potential of improved ICE engine technologies. If they did, they would be about 44% more fuel efficient than spark ignition ICEs and compression ignition ICEs. Taking into account the improvement of ICE technologies, achieving the full potential of spark ignition ICE-hybrid vehicles is estimated to cost about USD 3 000 per vehicle. These costs could be reduced by about 10% in the longer term. Similar calculations for compression ignition ICE-electric hybrids lead to an incremental cost estimate of about USD 4 500 per vehicle, eventually declining by 15%.

Plug-in electric hybrids (PHEVs)

PHEVs offer the same benefits as hybrids (improved ICE performance, regenerative braking, engine shut off in congested traffic, lower transmission losses, etc.), combined with the opportunity to drive in a pure-electric mode. They can be seen as a strengthened hybrid that relies more on the electric components. As for hybrids, some of the fuel economy improvements of PHEVs are partially offset by the additional weight due to the need for electric components, including motors and batteries.

Table 3.6 illustrates fuel economy potentials and costs for a plug-in configuration in which motion is entirely delivered through electric components over a driving range included between 30 km and 40 km. In such cases, the electric motor should have the same power requirements of the ICE (75 kW), and the batteries should be calibrated in order to allow the storage of enough energy to cover the 30 km to 40 km range while also being able to supply sufficient power for the motor at peak load.

As for hybrids, the cost of fuel economy improvement delivered by PHEVs is mainly associated with the battery pack. The batteries considered for the estimation of the costs presented in Table 3.6 store about 8 kWh of energy (6 kWh in the long term). Their cost is close to USD 650/kWh when using Li-ion technologies.

The incremental cost of a spark ignition PHEV with respect to a conventional ICE powertrain is close to USD 7 000 per vehicle (excluding development costs). This

Table 3.6 ► **Costs and improvement potentials for plug-in ICE-electric hybrids relative to a spark ignition engine in 2000-2005**

	Improvement potential (% reduction in fuel use, cumulative)		Cost (USD/vehicle, incremental)	
	Near term	Long term	Near term	Long term
Spark ignition ICE electric plug-in hybrid powertrain				
Emission control	-1%	-1%	100	110
Atkinson cycle	2%	1%	190	220
Reduced engine friction	2%	2%	250	220
Advanced cooling circuit + electric water pump	4%	3%	370	320
Plug-in hybrid system	47%	49%	6 710	4 210
Gasoline engine, GDI stoichiometric	47%	52%	6 710	4 840
Gasoline engine, VVLT or GDI stoichiometric	49%	54%	6 990	5 130
Compression ignition ICE-electric plug-in hybrid powertrain				
Emission control	-1%	-1%	200	240
Reduced engine friction	0%	-1%	270	240
Advanced cooling circuit + electric water pump	1%	0%	390	340
Plug-in hybrid system	41%	46%	6 720	4 220
Diesel engine today	50%	53%	8 290	5 410
Advanced diesel engine	50%	55%	8 290	5 940

may decrease to about USD 5 100 once battery costs decline. Table 3.6 presents complementary estimates for the case of compression ignition PHEVs.

The size of the electrical motor and the battery capacity for PHEVs can be significantly below the levels needed to provide full power requirements (Table 3.6) by using the ICE to help provide peak power. Batteries also do not have to provide energy for the full driving range of the vehicle. Lower power requirements allow calibration of batteries towards energy storage, requiring fewer cells (and therefore lower costs) for the same range. Lower pure-electric driving ranges could also cut further the battery size and cost. Typical plug-in costs could therefore range between the values presented in Table 3.5 and Table 3.6, depending on the characteristics chosen by manufacturers.

A vehicle concept that can help bridge the gap of low EV range is the “range extender”. This is basically an EV with a small ICE used primarily as an electricity generator to recharge the batteries and help sustain vehicle operation beyond the range provided by the batteries. The ICE is far smaller (and less expensive) than in a conventional PHEV. This could also allow a small reduction in battery capacity, to help pay the cost of the ICE addition.

Box 3.1 ► Battery characteristics and costs

Li-ion batteries appear very likely to become the dominant battery for vehicle applications within a few years, initially being introduced on PHEVs and EVs. They will then be expected to appear on conventional hybrids and, in time, as the standard battery on all LDVs.

Costs are expected to decline over time, once the demand for such batteries reaches a critical mass. For example, if four manufacturers order batteries from the same supplier for four new EVs each with initial projected sales of 25 000 units, the total battery production of 100 000 units should be sufficient to allow relatively full economies of scale to be achieved. With high-volume production, beyond 100 000 units (and up to millions, eventually), Li-ion batteries designed for EVs with a 150 km range appear likely to cost in the order of USD 500/kWh. With learning and optimisation, this is expected to drop to below USD 400 by 2015 or 2020, depending on the cumulative number of EVs produced over this time period. Costs of Li-ion batteries for plug-in hybrids will be higher per kWh, as these will need to be designed with greater power density, and battery costs rise with power density. For conventional hybrids, the cost per kWh will likely be higher still.

Table 3.7 provides an overview of the characteristics and estimated costs of different battery options for different vehicles.¹⁰ Long-term cost reductions are a result of increased scale of production, learning, increased optimisation of power-to-energy ratios, and optimised cell performance.

Total battery costs per vehicle are based on multiplying the estimated cost per kWh by the battery capacity needed for each type of vehicle. A Li-ion battery suitable for a conventional hybrid vehicle is expected to cost in the order of USD 900/kWh in the near term, dropping over time (and once production volumes increase to about 100 000 packs) to less than USD 700/kWh and eventually reaching USD 460 for very large production volumes. With vehicles needing about 1 kWh of storage capacity, total battery costs for conventional hybrid vehicles are likely to be close to USD 1 000 at present. Considering cost reductions on advanced vehicles with configurations that require only about 0.5 kWh, costs are expected to decline to USD 200 to USD 300 per vehicle battery pack.

For PHEVs, batteries are estimated to cost up to USD 6 000 in the near term for battery packs of 8 kWh, sufficient for a range of 30 km to 40 km on electricity alone. Significant increases of production volumes and improved battery characteristics are expected to bring costs down to about USD 420/kWh. In this case, the total cost of a set of battery packs could drop to USD 3 000 or less. Such a battery would weigh roughly 30 kg to 50 kg.

EVs, with a higher energy-to-power ratio, will need much larger battery capacities. Battery costs per kWh will likely be around 25% to 35% lower than those for conventional hybrids and about 15% to 30% lower of those for PHEVs. A mass-produced Li-ion battery pack sized to deliver about 30 kWh, giving a driving range of around 150 km, is expected to cost around USD 500/kWh to USD 600/kWh in the near term, equivalent to a total cost of USD 16 000 to USD 20 000 per vehicle. As volumes increase and with learning, a more fully optimised battery will eventually cost

10. Differences in battery costs for different vehicle types (i.e. hybrids, PHEVs and EVs) in this analysis are based on the assumption that the cost of each cell is essentially the same for all batteries, but that the power-to-energy ratio required in each case determines the specific battery costs per unit kWh or kW.

Table 3.7 ► Characteristics of batteries for different vehicles

	Battery	Timeline	Energy	Power	Weight	Specific costs		Total cost
			(kWh)	(kW)	(kg)	(USD/kWh)	(USD/kW)	(USD)
Conventional hybrid	NiMH	Near term	1.0	45	35-50	750-830	16-18	750-830
	NiMH	Long term	0.5	45	30-40	560-640	5.5-6.5	250-290
Conventional hybrid	Li-ion	Near term	1.0	45	15-25	760-1 000	17-22	760-1 000
	Li-ion	Long term	0.5	45	10-20	460-700	4.5-7	210-320
Plug-in hybrid	Li-ion	Near term	8	75	45-65	570-755	59-80	4 600-6 000
	Li-ion	Long term	6	75	30-50	420-645	33-52	2 500-3 900
Electric LDV 150 km range	Li-ion	Near term	33	75	180-240	470-620	230-300	16 000-20 000
	Li-ion	Long term	27	75	130-200	350-530	120-190	9 000-14 000
Electric LDV 200 km range	Li-ion	Near term	44	75	235-315	445-590	300-400	20 000-26 000
	Li-ion	Long term	36	75	170-270	330-505	160-240	12 000-18 000
Electric LDV 400 km range	Li-ion	Near term	88	75	415-555	405-535	520-700	36 000-47 000
	Li-ion	Long term	72	75	310-470	300-460	290-440	22 000-33 000

less, maybe USD 400/kWh to USD 500/kWh by 2015-2020. In the longer term (i.e. 2020 and beyond), a high-volume cost target of USD 350/kWh seems reasonable for a 150 km EV. Larger battery packs, suitable for EVs with longer ranges (e.g. 400 km), could cost even less per kWh, but given the capacity of the battery packs that would be needed in such vehicles, these would still be large, heavy and expensive.

Electric vehicles

EVs benefit from the high efficiency of electric motors. However, EVs are affected by the need to store energy in batteries. As illustrated in Box 3.1, this translates into important burdens in terms of weight and costs.

This analysis identified a typical EV as a vehicle equipped with a mass-produced Li-ion battery pack sized to deliver about 30 kWh and giving a driving range of around 150 km. Such a battery pack is expected to cost around USD 500/kWh to USD 600/kWh in the near term, equivalent to a total cost of USD 16 000 to USD 20 000 per vehicle. It is expected to weigh about 150 kg to 200 kg.

As volumes increase and with learning, a more fully optimised battery will eventually cost and weigh less, maybe USD 400/kWh to USD 500/kWh by 2015 to 2020 and only 150 kg. In the longer term (*i.e.* 2020 and beyond) a high-volume cost target of USD 350/kWh seems reasonable for a 150 km EV. Such evolution would reduce the incremental battery cost for 150 km EV to roughly USD 7 500 with respect to the Baseline spark-ignition ICE vehicle considered here. Some additional savings result from removal of the ICE engine and fuel system, though savings are offset by the addition of the electric motor/control system. Larger battery packs, suitable for EVs with longer ranges (*e.g.* 400 km), could cost even less per kWh. However, given the storage capacity that would be required in such cars, the size and weight of the battery packs would be large, and their total cost would be very high.

Given the cost and weight penalties of battery packs, pure EVs are unlikely to offer long ranges. Yet, EVs may emerge as symbols of an advanced mobility paradigm particularly suitable for urban areas. They may emerge as quiet, safe, highly desirable cars generating impressively low urban pollution, and offering a range of electronic tools and features.

Urban EVs may be smaller, lighter and more efficient than assumed here. If, for example, EVs with an efficiency of 0.1 kWh/km (in use) can be achieved, such EVs will require only half the battery capacity of those analysed here (which are at about 0.2 kWh/km). For this to occur, vehicles will need to have radical new designs, be far lighter, and perhaps have lower power than today's typical vehicles.

If small, very efficient EVs are marketed, similar ICE vehicles also could be. These could still have significant advantages in terms of range and first cost. Such cars could probably be "wired" like EVs (*i.e.* they could be provided with the same communication tools), and they would rely on much smaller engines (and therefore have much lower consumption when compared with today's vehicles) because of their limited size and weight. Thus, it is unclear whether EVs could "capture" an innovative urban car niche, or if they will even be marketed in this manner.

EVs are also likely to require fast charging stations in cities or along certain corridors. The additional investments needed are also likely to further determine the consumer acceptance and widespread introduction of EVs. A limited investment for the development of adequate infrastructure could constrain the widespread introduction of EV.

The successful market introduction and commercialisation of EVs will therefore require strong policies, such as support for recharging infrastructure expansion,

financial incentives for vehicle purchase, and well organised “roll-out” strategies to ensure that vehicles and infrastructure appear in similar locations. The IEA is concurrently preparing an EV-PHEV roadmap report that will explore these issues and propose strategies, to be published in Autumn 2009.

Fuel cell vehicles (FCVs)

Like EVs, FCVs benefit from the high efficiency of electric motors. FCVs are likely to be FCV-EV hybrids in order to best exploit the high efficiency potential of fuel cell systems. As a result, they will also benefit from the possibility to recover energy while braking.

Since reformers are likely to be limited by high costs and technical hurdles, FC-EV hybrids are assumed to rely on compressed hydrogen tanks (with a pressure of 35 MPa) in order to store the required energy. Liquid storage, pursued at the moment by one vehicle manufacturer, has not been taken into account in this analysis.

Table 3.8 summarises the cost estimates and the potential fuel economy benefits associated with FC-EV hybrids based on the analysis of several key literature sources addressing specifically these issues.

The cost of a FC-EV hybrid would derive from three key components: the fuel cell system (dominated by the fuel cell stack, and particularly by its electrodes and their platinum coating); the hydrogen storage reservoir; and the components required for the hybridisation of the vehicles (including electric motor and batteries).

Future cost reductions can derive from the cost reduction of the hybrid system components, reductions of the platinum loading in fuel cell electrodes (these are limited by their impact on the fuel cell efficiency and power density), and the development of non-platinum based fuel cell catalysts. Additional cost reductions could be associated with the high-volume production of storage tanks. Since the

Table 3.8 ► **Costs and improvement potentials for FCV relative to a spark ignition engine in 2000-2005 (FC-EV hybrid configuration)**

	Improvement potential (% of fuel consumption of the baseline vehicle, cumulative)		Cost (USD/vehicle, incremental)	
	Near term	Long term	Near term	Long term
Fuel cell - EV hybrid system	61%	66%	13 340	7 510
Fuel cell (stack, including platinum), smaller and more efficient (part load)			9 720	4 560
Hydrogen storage (35 Mpa)			1 710	1 710
Balance of plant			180	180
Hybrid system: electric motor and transmission			1 730	1 060

estimates found in literature seem optimistic, given the complexity of the tank manufacture, conservative values have been taken into account in Table 3.8.

Beyond cost-related issues, there are significant barriers dividing laboratory development from market diffusion of FCVs. The main one is the nearly complete lack of fuel distribution and production infrastructure. Another is the less evolutionary nature of fuel cell technologies with respect to an increased electrification of vehicles, which makes a switch towards FCVs more disruptive for the industry.

Several factors contribute to make a significant uptake of FCVs likely to require a strong combination of consumer preference over EVs and political will to develop, especially in the case of LDVs. Such factors include high vehicle costs, infrastructure-related barriers, the more disruptive nature of the technology and hydrogen costs that are likely to be higher than the cost of electricity, combined with the little advantages of FCVs with respect to noise and pollutants.

Additionally, the “chicken or egg” issue – limiting the diffusion of the technology to small niches until a sufficiently large infrastructure is in place – increases the scale of the upfront economic and political investment required for the diffusion of FCVs. Even if the costs of deploying a distribution network are not prohibitive to the success of FCVs, the large up-front investment heightens the risk of failure in case actual FCV development does not align with the expectations, thus creating an additional barrier for their development.

Fuel cells offer significant GHG mitigation options when hydrogen is produced from low GHG sources. Their cost is also expected to be similar (or lower) to the one of EVs and their range clearly superior (these are the reasons why they have been included as a possible option in the BLUE scenarios). Nevertheless, the likelihood of FCVs emerging as a future low carbon option for transportation is less evident than the probability to see a switch towards EV.

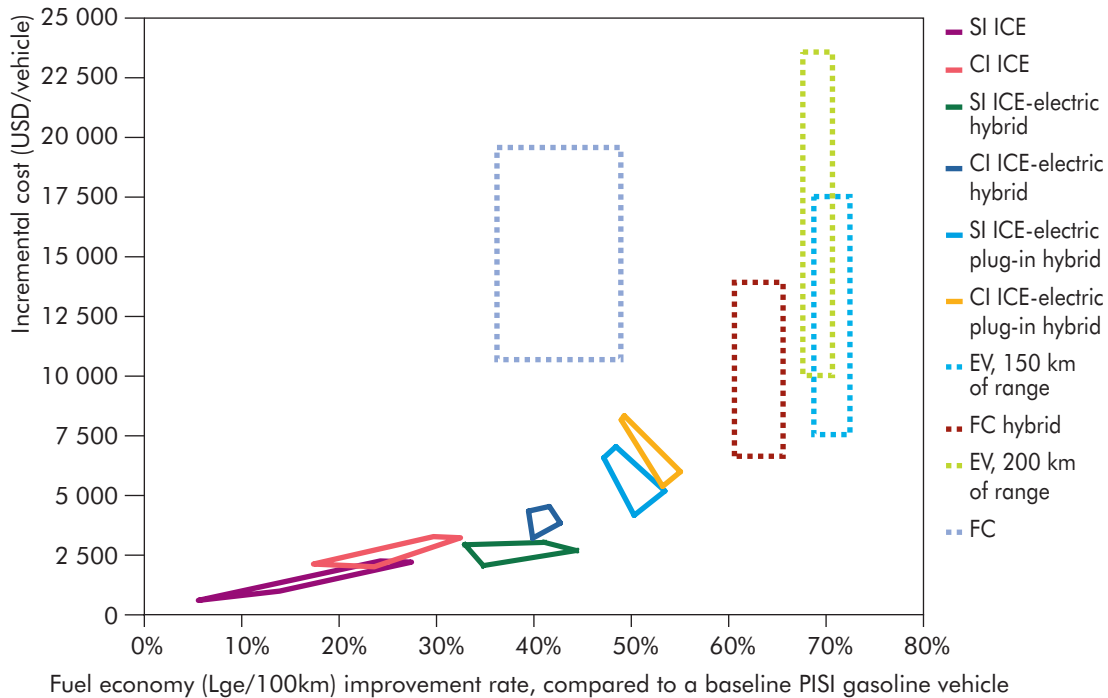
Summary of powertrain fuel economy and costs

Figure 3.19 shows estimated cost curves for a range of conventional ICEs, hybrids, and FCVs and hybridised FCVs.¹¹ Costs and improvement potentials are expressed relative to the efficiency of a vehicle using a conventional spark ignition ICE, *i.e.* around 25%. All costs assume large-scale production. Both near and longer term costs are included, reflecting optimisation and learning over time. Most technologies appear to have the potential to reach the lower range of their costs in the 2015 to 2020 time frame, if not sooner.

The estimates in Figure 3.19 refer only to vehicle fuel efficiency. They do not reflect the carbon intensity of different fuels. They take into account the improvements to the efficiency of the engine and drivetrain, the contribution of lower idling and regenerative braking, and the significantly better efficiency of electric motors and fuel cells, where relevant.

11. The fuel cell stack is assumed to have an efficiency of 70% in hybrid versions and an efficiency of 40% to 50% when the fuel cell vehicle is not hybridised.

Figure 3.19 ▶ Comparative incremental costs and potentials of different powertrain technologies



Note: CI = compression ignition; SI=spark ignition; PISI=port injection spark ignition.

Source: IEA analysis.

Key point

Different powertrain technologies are associated to different cost and tank-to-wheel GHG mitigation potentials. Improvements to conventional ICEs are cheapest; EVs and FCVs are the most expensive.

Fuel cell hybrids and EVs stand out because of the significant efficiency improvement that they can deliver. But they are also very expensive. EVs offer better efficiency potentials than any other options, but they will be limited in driving range if costs are to be contained.

Conventional ICEs, hydraulic and electric hybrids, and EVs form a potential evolutionary path for the delivery of better fuel economies at gradually increasing cost. This evolutionary path also provides a potential route to electricity becoming the main source of transport power, which could eventually deliver near-zero GHG emission driving on a life-cycle basis as envisaged in the BLUE Map scenario. Hydrogen FCVs can also potentially achieve this, but the pathway is not evolutionary. Rather, it would require a very significant change in current vehicle designs and the development of a completely new and very expensive refuelling infrastructure.

Switching to electric or hydraulic hybrids will increase vehicle costs significantly. Reducing the level of hybridisation, for example by using a smaller battery/motor system, can help bridge the cost gap but this will not deliver as much in terms of better efficiency. Thereafter, PHEVs may offer the next step up in the evolutionary pathway, by running on batteries charged from the grid for part of the time in a mode that is approximately three times as efficient as running in ICE mode.

Figure 3.19 is based on a particular configuration of PHEV, where 40% to 50% of the total travel is driven in the EV mode. Many other configurations are possible, e.g. with more or less battery storage. The cost and the efficiency improvements delivered by plug-ins can vary significantly according to the configuration adopted. A low-range PHEV, for example capable of 10 to 20 km on a single charge, might provide an attractive combination of price and fuel efficiency for drivers who have relatively low average daily travel patterns.

Non-engine technologies: fuel economy potentials, costs and emissions

Aerodynamic drag

Aerodynamic streamlining does not typically require additional materials, although it may need new types of material. Aerodynamic streamlining for new models, (e.g. with spoilers, front air dams, side skirts and underbody panels), will require investment in design and styling, but these are unlikely to be significant in terms of costs per vehicle. Overall, a slow but ongoing trend towards improvements in aerodynamics should be possible at relatively low incremental cost per unit of energy savings.

Tyres

There is little historical correlation between the rolling resistance (RR) of tyres and their price. This might suggest that the savings associated with technical improvements in tyres could come at a very low cost. But tyres are purchased with a variety of goals in mind, including performance and safety, and pricing may be a poor indicator of manufacturing cost. Improvements in rolling resistance could be achieved at a cost of around USD 40 per vehicle, declining to USD 20 per vehicle in the medium to long term. Tyre pressure monitoring systems can also be introduced at a cost of around USD 20 to USD 30 per vehicle, since the only change they would require is the introduction of an additional sensor per wheel or the integration of the information collected from other sensors. Taking these items together, the total cost associated with the 5% improvement potential estimated for tyres is around USD 40 to USD 70 per vehicle.

Lighting

Although xenon lamps are far more efficient than halogen headlamps, they are expensive. On average they appear likely to cost in the order of USD 350 to USD 400 per vehicle (Table 3.9).

Table 3.9 ► Costs and potentials of different lighting technologies

	LED	Xenon
Cost vs. halogen (USD/vehicle)	760	380
Potential vs. halogen (%)	40-80	65-70

White LEDs currently cost more than xenon lights with the same performance, but their potential for cost reduction is expected to be much stronger. As a result, white LEDs may become an increasingly interesting solution for headlights (also delivering fuel efficiency improvements) if very significant cost reductions take place. Meanwhile, given their suitability as daytime running lights, LEDs offer significant near-term energy savings in this application.

Air-conditioning systems

Improved MAC systems could save 3% to 4% of vehicle fuel use in areas where air conditioning is used a significant percentage of the time. The additional cost of an improved MAC system appears to be fairly low, of the order of USD 30 to USD 50. Higher incremental costs, probably in the range of USD 100 to USD 200, would be associated with MAC systems using CO₂ as refrigerant fluid mainly because CO₂ needs to be operated at a higher pressure, close to 5 bar.

Material substitution

An optimised steel body with significant shares of HSS and AHSS could reduce vehicle weights by roughly 10% compared to today's vehicles. The cost of such reductions has been estimated between zero, taking account only of vehicle costs, and about USD 300 per vehicle, taking account of maintenance costs associated with the use of more resistant steel. A 10% reduction in total vehicle weight would save approximately 6% of the fuel consumed by a conventional spark ignition engine. The saving would be less for more efficient powertrains, since downsizing would deliver smaller fuel savings.

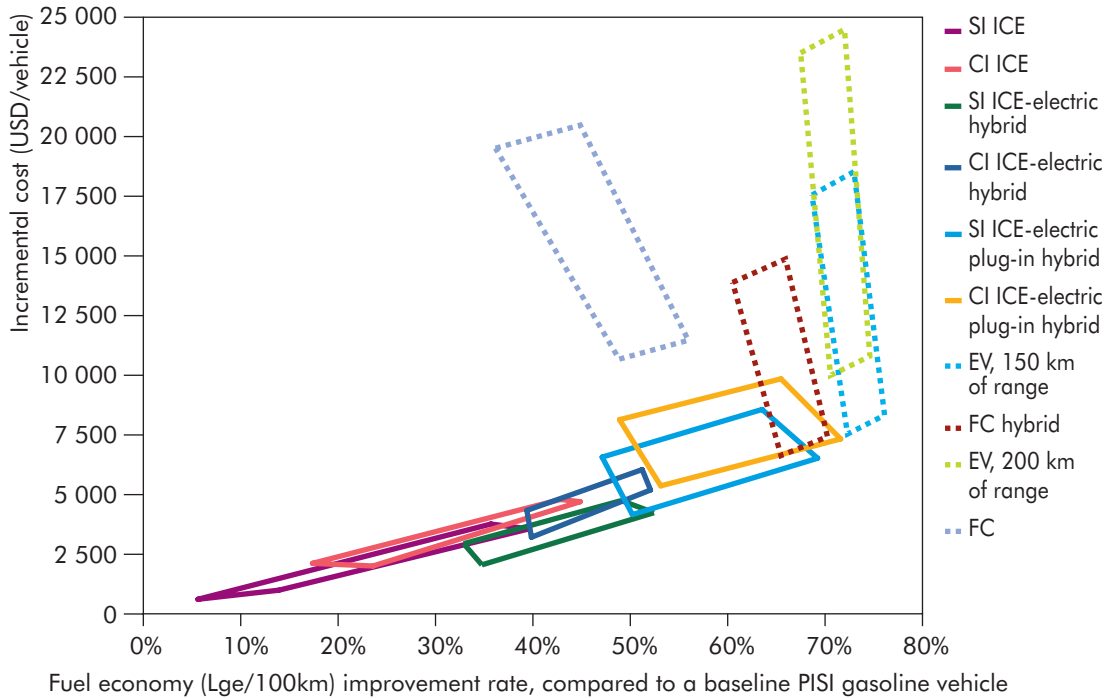
Aluminium has the potential to save about 12% to 25% of the weight of components in which it is used. A 25% weight reduction would deliver around 15% fuel savings in a conventional spark ignition vehicle and about 10% on a hybrid. Although some of these savings could be achieved at low cost, achieving the full 25% weight reduction would be likely to cost in the order of USD 1 200 to USD 1 500 per vehicle.

Composite materials consisting of a glass- or carbon fibre-reinforced polymer could deliver very significant weight savings of between 35% to 40% of the total vehicle weight. The greater use of fibreglass could save around 25% of the total weight. But the extensive use of composite materials would add around USD 20 000 per vehicle. High cost, and the difficulty of manufacturing vehicles with extensive composite materials, makes it very unlikely this will be widely pursued.

Comparison of vehicle costs and fuel economy improvement

Taking into account both the engine/drivetrain and non-engine components, a range of possible fuel consumption improvements and costs for different vehicle types is shown in Figure 3.20. The inclusion of non-engine efficiencies in the cost curves for each powertrain technology (elaborated in Figure 3.19) leads to significant increases in the total potential fuel reductions but also increased costs.

Figure 3.20 ▶ Incremental costs and potentials of different powertrain technologies, including non-engine technologies and material substitution



Note: CI = compression ignition; SI=spark ignition; PISI=port injection spark ignition.

Key point

Once powertrain technologies are coupled with other vehicle technologies, costs and GHG mitigation potentials increase. The effect of non-engine technologies and material substitution is does not alter much the relative performance of different solutions.

Taking all components together, hybrids could achieve about a 50% improvement in vehicle fuel economy at a cost of around USD 4 000 per vehicle. To go beyond a 50% improvement in fuel economy, the next step may be to move towards PHEVs, which could achieve up to 70% improvements at a cost of around USD 7 500 per vehicle.

Hybridised FCVs can reach a better level of fuel efficiency than PHEVs, but are also likely to be significantly more expensive, especially in the nearterm. They also offer the possibility of very low CO₂ emission driving if the H₂ is derived from low CO₂ sources. Very low CO₂ driving for PHEVs will be limited to the distance they are driven on electricity rather than on the ICE, and the CO₂ intensity of electricity generation. Electric driving share is assumed to remain below 50% on average.

The greatest efficiency improvements come from pure EVs, offering up to nearly an 80% reduction in energy intensity compared to a current conventional spark ignition ICE. But for EVs with a range of around 150km, the battery costs are likely to remain over USD 10 000 for at least some years. For long-range EVs, even with a range still well below today's ICE vehicles or a plug-in hybrid, the incremental vehicle cost is likely to exceed USD 20 000.

Cost-benefit and CO₂ reduction cost

A critical question for future policy development is the extent to which these technology options are justified in the near and longer term, both in terms of economic costs and of the cost per tonne for the CO₂ reductions they achieve.

This analysis looks at these issues from two perspectives. The assumptions used in the two approaches are shown in Table 3.10. The first approach adopts a societal cost analysis. This reflects the fact that, in reducing CO₂ emissions, society is addressing a long-term problem that would not be justified by a near-term perspective. To reflect this, a low discount rate (3%) for the future is taken. In addition, since the analysis is “normative” (i.e. prescriptive rather than descriptive as in the private cost analysis), it is appropriate to use real economic costs for vehicles and fuels, and to exclude taxes (since taxes do not reflect real economic costs, only wealth transfers within society).

Table 3.10 ► Assumptions for the cost-benefit analyses

	Societal cost analysis	Private cost analysis
Discount rate	3%	(payback period)
Average vehicle life	15 years	15 years
Average travel over vehicle life, undiscounted	200 000	200 000
Average travel over vehicle life, discounted	168 000	n/a
Fuel tax per litre	None	Based on CO ₂ tax of USD 50/tonne (thus variable on an energy basis by fuel), on top of a 60% fuel tax (VAT)
Fuel cost per litre without tax	Two cases, based on oil price of USD 60/bbl and USD 120/bbl, used for both private and societal analysis, resulting in untaxed fuel prices of about USD 0.50/L and USD 0.90/L for gasoline, USD 0.08/kWh to USD 0.16/kWh for electricity, and USD 0.50/L to USD 0.80/L of gasoline equivalent for hydrogen	
Baseline on-road fuel economy	9.5 Lge/100km	

The second approach, a private cost analysis, considers payback periods. Consumers may be hesitant to purchase more expensive vehicles, even if these vehicles provide fuel savings, if the savings do not pay back in a fairly short period of time, perhaps three to five years. Consumers also face market prices that, in most countries, include significant fuel taxes. A 60% fuel tax rate for all fuels represents the global average value-added tax on fuel today (GTZ, 2008). In addition, a CO₂-based fuel tax of USD 50/tonne is applied to different vehicles and fuels on the basis of their well-to-wheel emissions. Biofuels, electricity and hydrogen are also subjected to the same taxation scheme.¹² Several H₂ production pathways

12. Even though a 60% tax rate is significantly higher than the average rate applied today in the case of electricity or hydrogen use, the analysis carried out here is based on such rates for all energy carriers in order to create a level playing field and to avoid tax revenue losses that would otherwise occur from a major switch towards non-conventional options.

and electricity generation mixes have been considered, in order to establish the relevance of alternative pathways for both electricity prices and CO₂ emissions.

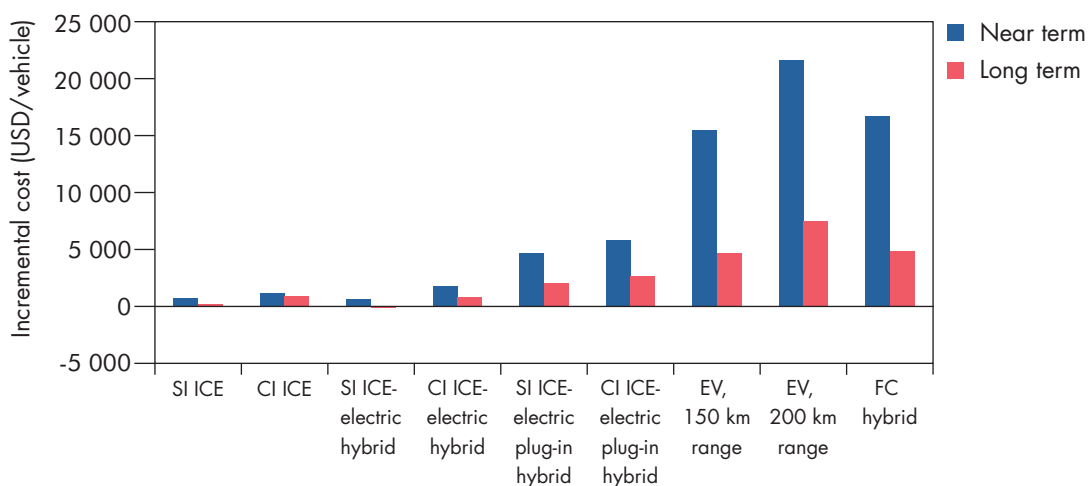
Finally, two oil prices are considered, USD 60/bbl and USD 120/bbl. These are translated into retail fuel prices based on the analysis presented in fuel cost Case 3 in Chapter 2. Vehicles are compared to a base 2005 vehicle with tested fuel economy of 8 Lge/100 km and an actual on-road fuel economy of 9.5 Lge/100 km. For plug-in hybrids, a maximum 50% of the total travel is assumed to be powered by grid electricity.

Societal cost analysis

For the societal cost analysis, four cases are presented: near-term and medium/long-term technology costs, combined with low and high oil prices. Figures 3.21 and 3.22 show the incremental vehicle and (discounted) fuel cost over the vehicle life for different technologies and fuels in the near and medium-long term. Figure 3.21 shows the results with oil at USD 60/bbl and Figure 3.22 shows results with oil at USD 120/bbl.

With oil prices around USD 60/bbl, no fuel tax and a societal discount rate of 3% (resulting in 168 000 km of lifetime vehicle travel), all vehicle/fuel technologies result in net cost increases in the near term, although advanced spark ignition vehicles and hybridised spark ignition vehicles are very close to break-even. In the longer term, all technologies/fuels do better as technology and fuel costs drop, with a few passing the break-even point (e.g. negative net costs meaning net monetary gains to consumers). Assuming higher oil prices around USD 120/bbl,

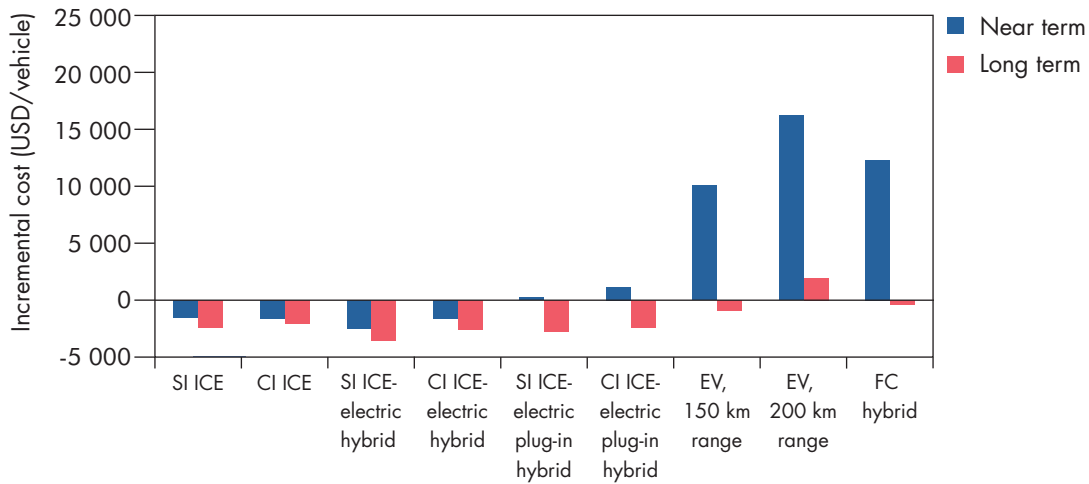
Figure 3.21 ► Incremental cost of vehicle over its lifetime with respect to the baseline PISI spark ignition ICE, societal analysis, with oil USD 60/bbl (near-term and medium- / long-term vehicle costs)



Key point

With oil at USD 60/bbl all vehicle/fuel technologies give net cost increases in the near term. Advanced ICEs and ICE-HEVs, however, lead to much smaller increases than other technologies. In the longer term, all technologies and fuels do better as technology costs diminish through learning and research.

Figure 3.22 ► Incremental cost of vehicle over its lifetime with respect to the baseline PISI spark ignition ICE, societal analysis, with oil at USD 120/bbl (near-term and medium- / long-term vehicle costs)



Key point

With oil at USD 120/bbl all advanced ICEs and ICE-HEVs provide net savings over their lifetime in the near term. In the longer term, all but 200 km range EVs deliver lifetime cost savings.

all advanced ICEs and ICE-electric hybrids lead to net savings over their lifetime in the near term. In the longer term, spark-ignition and compression ignition PHEVs also deliver lifetime cost savings. Limited range EVs and fuel cell hybrids also reach the break-even if future cost reductions for battery storage (described above) and fuel cell systems are achieved.

Private cost analysis

The same four cases are presented for the private cost analysis in Figures 3.23 and 3.24, using a payback period approach. These show the number of years for fuel savings to pay for the higher vehicle cost. Considering the USD 60/bbl cost estimates, in the near term most vehicle technologies are associated with payback periods greater than five years and all electric and fuel cell technologies above ten years. Though many factors influence consumer interest in purchasing different types of vehicles, the payback periods shown here suggest that most consumers will need incentives to be willing to make investments in the higher technology vehicles, all else equal. In the longer term, spark-ignition PHEVs also drop close to a five-year payback.

All technologies have much shorter payback periods when the oil price assumption is raised to USD 120/bbl. In the long run, nearly all options drop below a five-year payback rate, suggesting that incentives will become less important over time and as oil prices rise. The assumptions regarding vehicle and fuel costs are extremely important to these results. More pessimistic assumptions, for example less reduction in advanced technology cost in the future, could lead to considerably higher payback times.

The influence of a USD 50/t CO₂ tax in the overall payback time is rather small. As shown in Figures 3.23 and 3.24, in the case of a 150 km EV running with electricity produced from very different generation mixes, the influence of CO₂ taxes results in payback time variations that are included within one or two years.

CO₂ cost-per-tonne estimates

Applying life-cycle, well-to-wheel CO₂ emission factors for each fuel to the estimated fuel savings, and then comparing to the net costs as estimated in the societal cost analysis, allows CO₂ cost per tonne estimates to be made for each technology and fuel, compared to the base gasoline vehicle. The CO₂ emission factors presented in Chapter 2 are used for this purpose. Biofuels that can be used in conventional or advanced ICE engines have also been included in this comparison. For simplicity, these are assumed to be used in high volume, *i.e.* 100% blends, with spark ignition or compression ignition ICEs.¹³

In the analysis for EVs, four electricity generation mixes are considered:

- The US generation mix, where the use of coal as the primary energy source is relatively high.
- The average electricity generation mix of OECD Europe, more diversified and more reliant on natural gas and new renewables.
- The French electricity generation mix, characterised by a dominance of nuclear electricity and therefore a very low rate of CO₂ emissions per kWh. Similar CO₂ intensities can be achieved when renewable energy constitutes most of the primary source of energy for power generation (as in Brazil) or once low GHG technologies (including CCS, eventually) have been introduced.
- The Chinese generation mix, with a very high reliance on coal as the primary energy source, and a high carbon intensity.

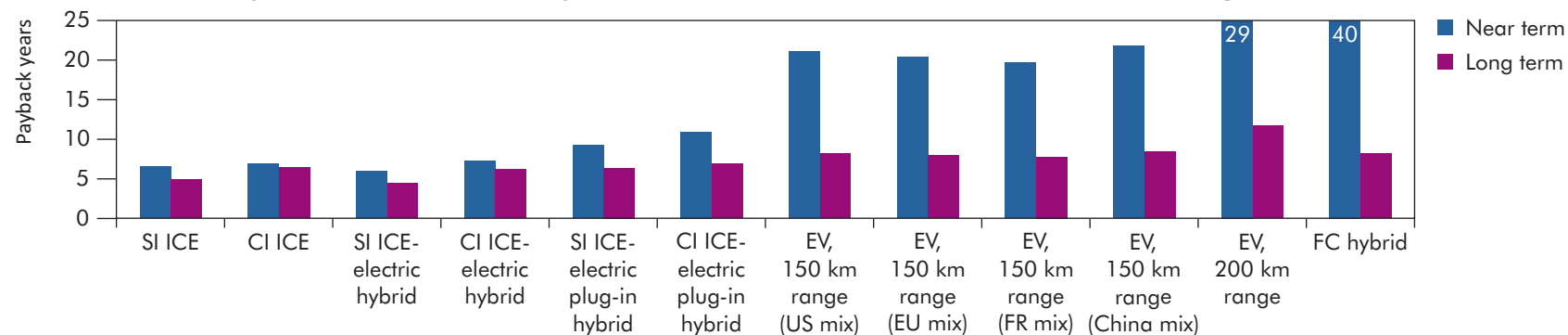
For FCVs operating on H₂, four cases are considered:

- H₂ from electrolysis with the US electricity generation mix.
- H₂ from electrolysis with the EU electricity generation mix.
- H₂ from electrolysis with a low overall GHG emission factor, as in the French or Brazilian electricity generation mix.
- H₂ from electrolysis with the Chinese generation mix, characterised by a high GHG emission factor.

Figures 3.25, 3.26, 3.28 and 3.29 show the lifetime incremental costs of vehicles and fuels as a function of the corresponding potential CO₂ savings. They cover a wide number of vehicle and fuel options, including biofuels (in combination with

13. For this comparison, biofuels have been assumed to replace entirely the relevant fossil fuel they compete with, and to deliver a GHG emission reduction that corresponds to the mid-point estimates retained in Chapter 2. A number of potentially important factors on biofuel GHG, such as land-use change, have not been taken into account. As a result, the data illustrated should be corrected if the production of biofuels leads to the conversion of land areas, taking into account appropriate changes of GHG emission factors.

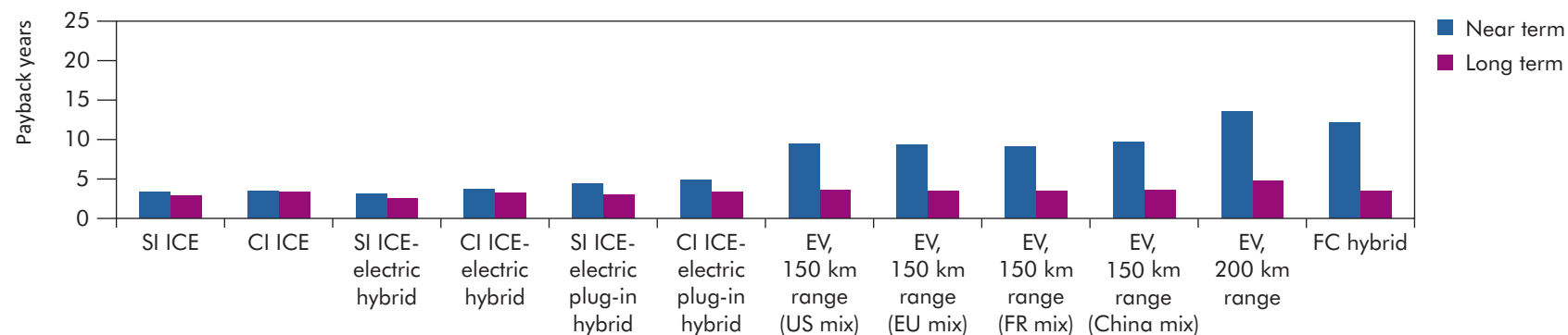
Figure 3.23 ▶ Payback period, private analysis, with oil USD 60/bbl (near-term and medium- / long-term vehicle costs)



Key point

With oil at USD 60/bbl in the near term, most vehicle technologies are associated with payback periods greater than five years. In this timeframe, advanced ICEs, ICE-HEVs and PHEVs do far better than other technologies. In the longer term, spark-ignition PHEVs also drop close to a five-year payback, while EV and FC hybrids become more attractive.

Figure 3.24 ▶ Payback period, private analysis, with oil at USD 120/bbl (near-term and medium- / long-term vehicle costs)



Key point

With oil at USD 120/bbl, all technologies have much shorter payback periods. In the long term, most of them – including 150 km EVs – reach paybacks lower than four years.

technological improvements on the advanced spark ignition and compression ignition ICE vehicles) and a set of representative electricity mixes, under different oil price assumptions. As for the cost analysis above, four cases are illustrated: near-term and long-term costs and potentials with USD 60/bbl and USD 120/bbl of oil. The cost per tonne of CO₂ saved corresponding to each of these vehicle and fuel options is presented in Figure 3.27 (USD 60/bbl of oil, near and long term) and Figure 3.30 (USD 120/bbl of oil).

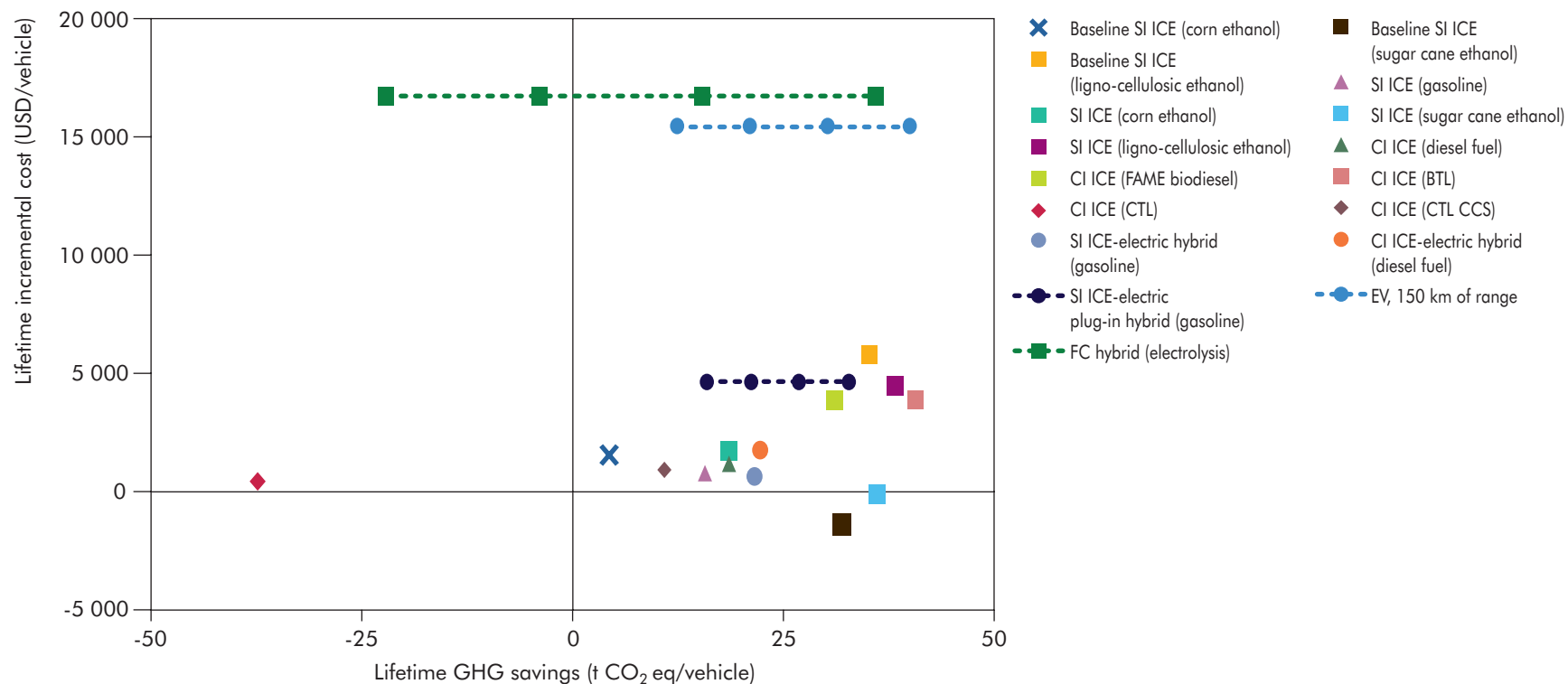
At USD 60/bbl oil, none of the vehicle/fuel options considered achieves CO₂ savings at a net negative cost per tonne saved in the near term, though several are below USD 100. The most cost-competitive, low-GHG biofuel (ethanol from sugar cane) is the only option delivering net savings, even in the short run. At these levels of oil price in the near term (Figure 3.25 and Figure 3.27), the cost per tonne of CO₂ saved ranges between USD 30/t and USD 80/t for advanced ICEs and ICE-hybrids (the values are lower when some biofuels are coupled with the advanced ICEs, and higher with other biofuels) and between USD 140/t and USD 300/t for plug-ins (the range accounts for the different electricity generation mixes, in this case). CO₂ mitigation costs are more than USD 400/t for most EV options.

Additionally, important changes with respect to the CO₂ saving potentials are associated with the electricity generation mix. Such changes are particularly relevant in the case of EVs and FCVs (when hydrogen is produced from electrolysis). The dotted lines in Figures 3.25, 3.26, 3.28 and 3.29 link typical electricity mixes for main regions such as the United States, the European Union, France (eventually Brazil), or China. For FCVs, the dotted lines link the lifetime GHG savings associated with the different hydrogen production processes. This shows the range of emission savings depending on the electricity grid and the way hydrogen is produced. The variation of CO₂ mitigation costs is so wide that displacing one tonne of CO₂ using EVs in coal-intensive power regions (such as China) turns out to be hundreds of USD more expensive than doing it in a region where low-carbon electricity dominates the generation mix. Feedstock production is similarly important for H₂ fuel FCVs. Some options, such as FCVs coupled with hydrogen production from electrolysis in carbon-intensive power generation regions, do not deliver any CO₂ reduction. In fact, they would actually contribute to increases of CO₂ emissions with respect to the base vehicle.

In the longer term, the situation changes towards lower CO₂ mitigation costs and less variability. The mitigation costs for advanced ICEs and ICE-hybrids is very close to zero USD/t in the case of spark-ignition ICE hybrids and advanced spark-ignition ICEs. Plug-in hybrids deliver CO₂ savings for as little as USD 60/t in the best cases, and in regions with low CO₂ power generation, EVs with 150 km range reach roughly USD 120/t. FC hybrids achieve values close to USD 140/t if they use hydrogen produced from low CO₂ electricity. For those H₂ feedstocks where FCVs provide net CO₂ reductions, hybridised FCVs provide much lower cost-per-tonne CO₂ reduction than non-hybridised FCVs. For this reason, conventional FCVs are not shown in any of the figures concerning lifetime vehicle costs and CO₂ mitigation costs.

Assuming higher oil prices (USD 120/bbl, Figures 3.28, 3.29 and 3.30), the picture is very different. All advanced ICE and ICE-hybrid vehicles provide CO₂ reductions at a net negative cost per tonne (*i.e.* resulting in net savings), compared to the base spark ignition ICE vehicle, even in the near term. Advanced ICEs and ICE hybrids

Figure 3.25 ▶ Lifetime incremental cost of vehicle and fuel combinations as a function of CO₂ savings, oil price at USD 60/bbl (near-term vehicle costs)

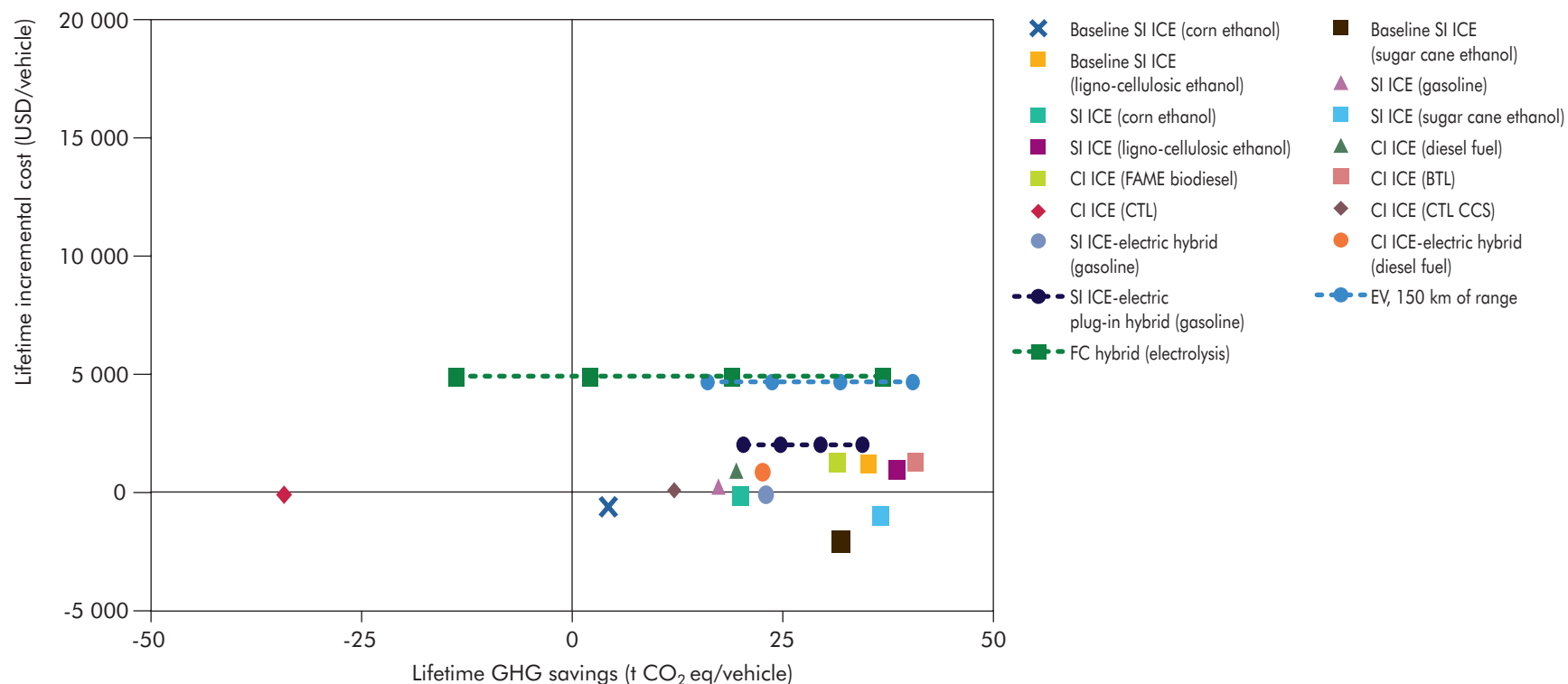


200 000 km, 3% discount rate, 15 years, 0.4 USD/Lge for oil-based fuels,
0.07 USD/kWh for electricity, 0.6-0.9 USD/kWh for biofuels

Key point

Most technologies lead to net GHG savings over the vehicle lifetime. In the near term and with oil price of USD 60/bbl, conventional ICEs and ICE-HEVs lead to incremental lifetime vehicle costs lower than USD 5000 per vehicle.

Figure 3.26 ▶ Lifetime incremental cost of vehicle and fuel combinations as a function of CO₂ savings, oil price at USD 60/bbl (medium- to long-term vehicle costs)

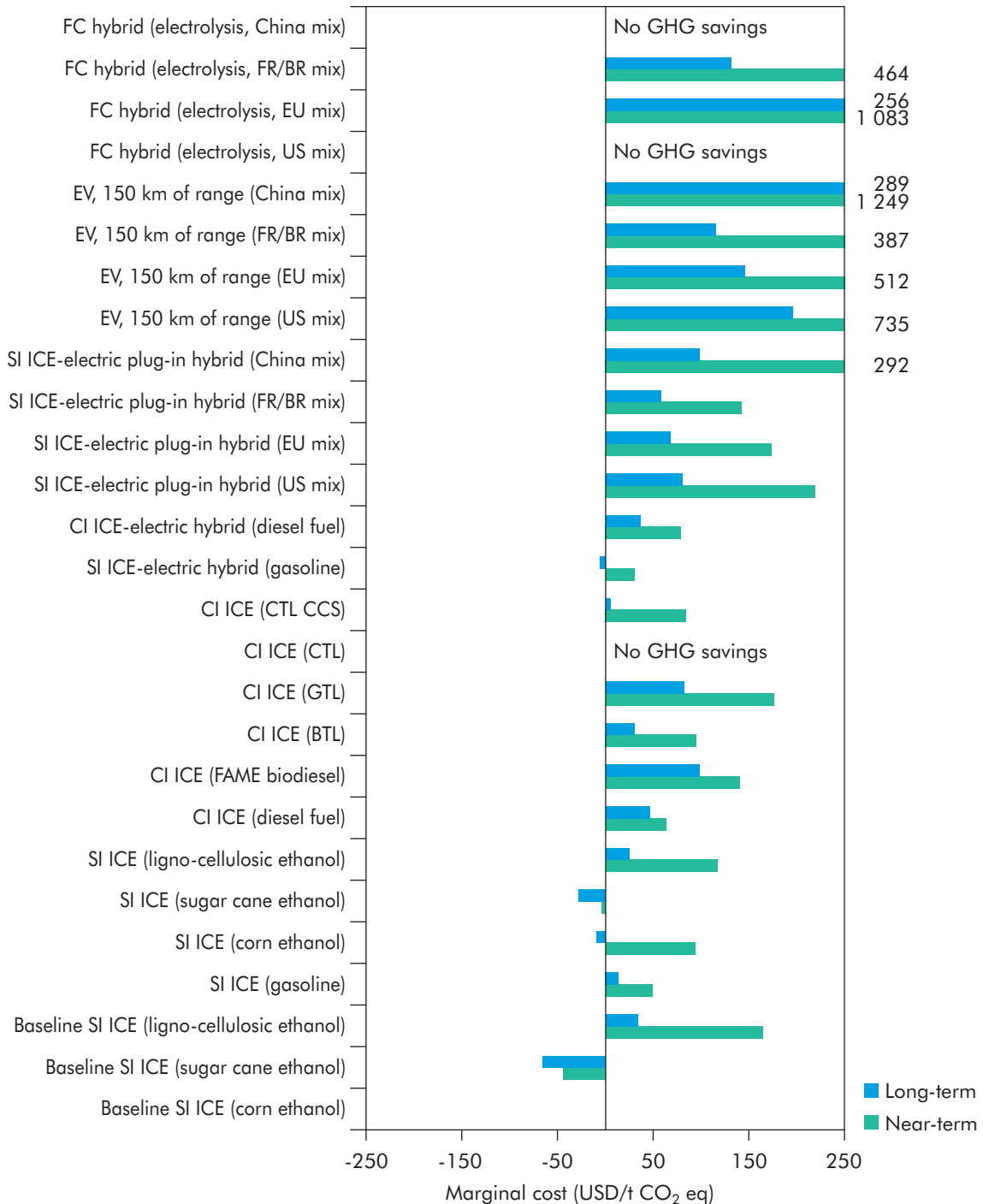


200 000 km, 3% discount rate, 15 years, 0.4 USD/Lge for oil-based fuels,
0.07 USD/kWh for electricity, 0.6-0.9 USD/kWh for biofuels

Key point

Technology learning is expected to lower significantly the lifetime incremental costs for all vehicle and fuel combinations, reducing the vehicle incremental lifetime costs below USD 2500 per vehicle for conventional ICEs and ICE-HEVs (and below USD 5000 per vehicle for all technology options) when the oil price is at USD 60/bbl.

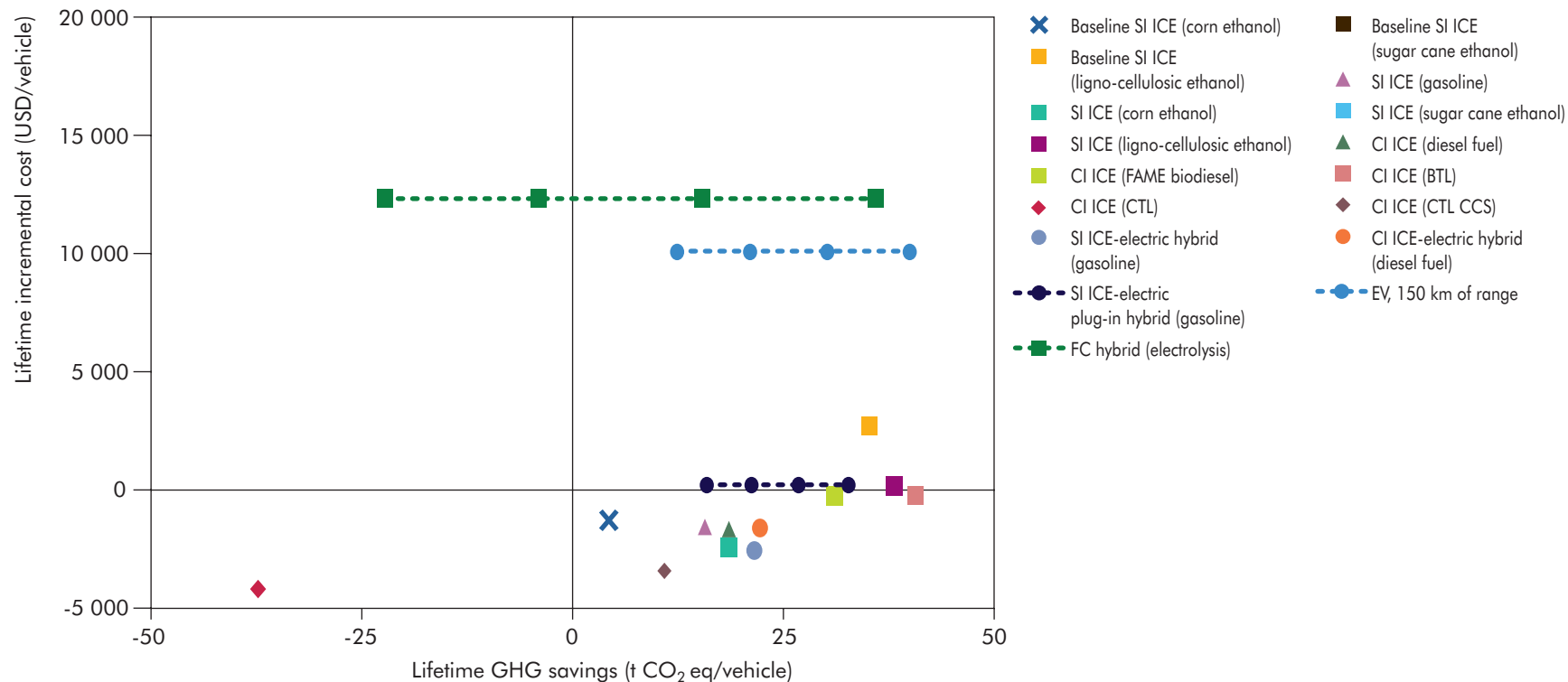
Figure 3.27 ► Cost per tonne of CO₂ saved over the vehicle life, oil price at USD 60/bbl (near-term and medium- / long-term vehicle costs)



Key point

At USD 60/bbl, CO₂ mitigation costs are lower than USD 50/t in the near term only for spark-ignition ICEs and spark-ignition ICE-HEVs. In the same timeframe, PHEVs deliver CO₂ savings for about USD 150/t with low carbon electricity. In the long term, CO₂ mitigation costs for spark ignition ICEs and ICE-HEV approach zero. GHG mitigation costs are also expected to attain about USD 50/t for PHEVs with low-carbon electricity, between USD 120/t and USD 300/t for 150 km EVs, and close to USD 150/t for FC hybrids using hydrogen produced from low-carbon electricity.

Figure 3.28 ▶ Lifetime CO₂ reduction and incremental cost of vehicle and fuel combinations as a function of CO₂ savings, oil price at USD 120/bbl (near-term vehicle costs)

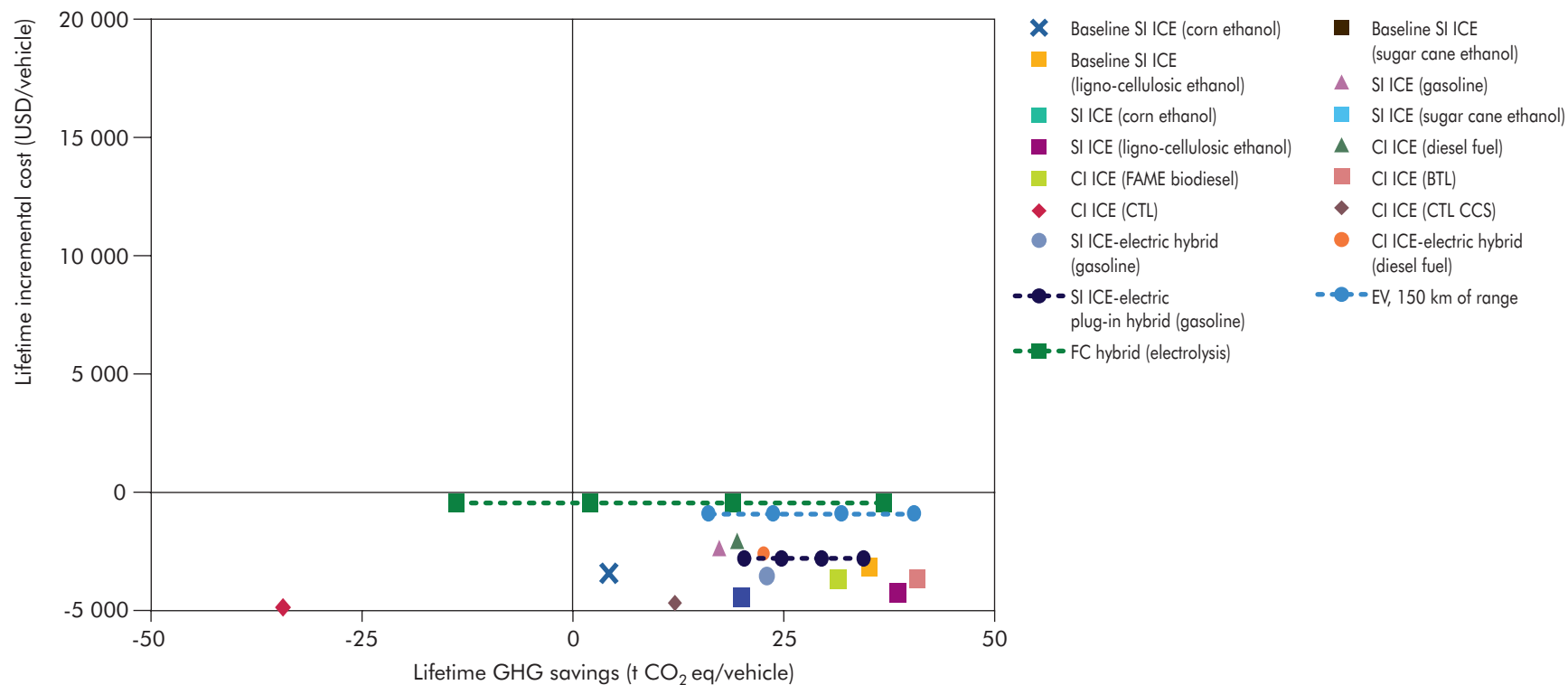


200 000 km, 3% discount rate, 15 years, 0.4 USD/Lge for oil-based fuels,
0.07 USD/kWh for electricity, 0.6-0.9 USD/kWh for biofuels

Key point

An oil price of USD 120/bbl limits the incremental lifetime costs for all vehicle and fuel combinations, even in the near term. The incremental lifetime vehicle costs of conventional ICEs, ICE-HEVs and PHEVs are zero or negative in this context. They are at USD 10 000 to USD 12 000 for FC hybrids and EVs.

Figure 3.29 ▶ Lifetime CO₂ reduction and incremental cost of vehicle and fuel combinations as a function of CO₂ savings, oil price at USD 120 USD/bbl (medium- to long-term vehicle costs)

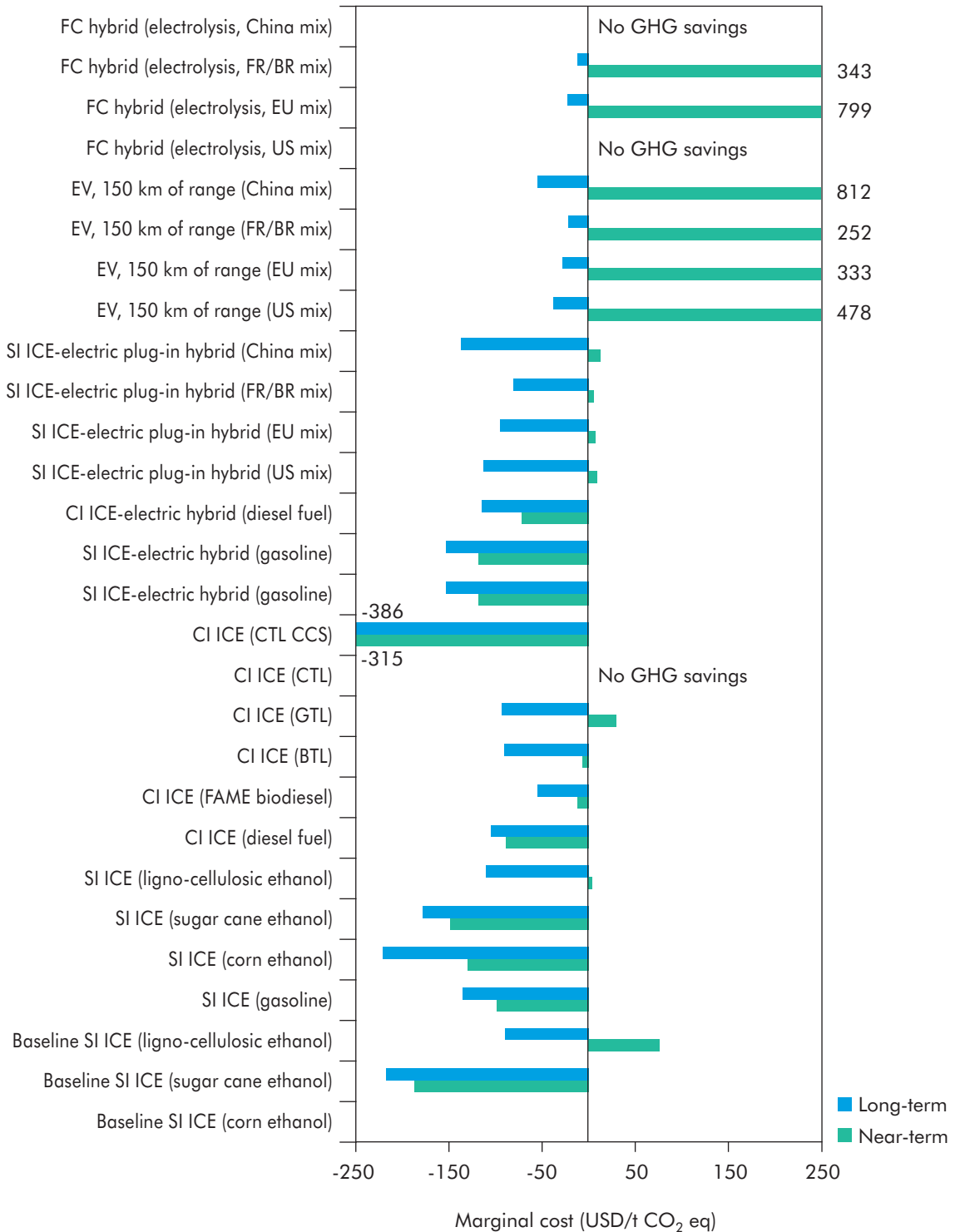


200 000 km, 3% discount rate, 15 years, 0.4 USD/Lge for oil-based fuels, 0.07 USD/kWh for electricity, 0.6-0.9 USD/kWh for biofuels

Key point

The combination of technology learning and an oil price of USD 120/bbl reduces the incremental costs for all vehicle and fuel combinations. CO₂ mitigation costs are zeroed out for EVs and FCVs, and negative for most of the remaining options (excluding CTL and hydrogen production from electrolysis based on a coal-rich electricity generation mix without CCS, which do not deliver any GHG saving).

Figure 3.30 ▶ Cost per tonne of CO₂ saved over the vehicle life, oil price at USD 120/bbl (near-term and medium- / long-term vehicle costs)



Key point

With oil price at USD 120/bbl CO₂ mitigation costs are lower than USD 50/t for PHEVs, and negative for ICE and ICE-HEV technologies. In the long term, EVs and FCVs also reach negative CO₂ mitigation costs.

lead to net savings even when coupled with corn ethanol. The combination of technology learning and an oil price of USD 120/bbl reduces the incremental costs for all vehicle and fuel combinations, even if they are as high as USD 10 000 to USD 12 000 to vehicle for EVs and FC hybrids in the near term.

Two important caveats are worth noting; one is that for vehicle/fuel combinations that provide CO₂ reductions at negative cost, a perverse effect can occur where options that reduce less CO₂ at a given cost look better than options with a larger CO₂ reduction. This is because an option that provides less CO₂ reduction at a given total negative cost shows up with a larger magnitude negative cost per tonne reduced than an option with more CO₂ savings. Thus, the relative magnitudes of negative cost-per-tonne estimates are not always reliable indicators of relative merit of fuels. But, of course, all options that achieve negative costs are economically superior to those with net positive costs.

The other caveat is that for the long term, it may make sense to compare new options to a future (rather than present) Baseline vehicle. This might be an advanced spark ignition ICE vehicle with characteristics as in the Baseline scenario, e.g. in 2020. This vehicle embodies many of the lower-cost incremental technologies and is about 20% more fuel efficient than the 2005 base vehicle. Therefore other technologies save less fuel and have higher incremental costs compared to this vehicle than when compared to the base vehicle.

As shown by the various cases, the results are quite sensitive to assumptions regarding oil price, time frame and feedstock characteristics. Small changes in relative cost or relative CO₂ emissions can, in certain instances, result in fairly wide swings in CO₂ cost per tonne. As mentioned, comparing negative CO₂ cost per tonne estimates is especially problematic, though negative values at least suggest very good opportunities to cut CO₂ emissions at low or negative cost.

Box 3.2 ▶ **A key finding: 50% fuel economy improvement is cost-effective**

Figures 3.25 and 3.26 show that, with an oil price of USD 60/bbl, a number of technologies – including advanced ICEs and spark ignition ICE hybrids – result in zero or near-zero long-term vehicle lifetime costs if the cost analysis is undertaken from a societal perspective. Figure 3.20, which shows incremental costs and potentials of different powertrain technologies, illustrates that ICE-HEVs have the potential to improve fuel economy (expressed in Lge/100 km) by more than 50%. The same figure shows that PHEVs and other technologies can achieve even better results.

These results are further reinforced by those presented in Figures 3.28 and 3.29, where the same vehicle technologies are analysed in a context where the oil price is significantly higher (USD 120/bbl). In this case, the introduction of advanced ICEs and spark ignition ICE HEVs would lead to net savings on a lifetime basis. Additionally, when the oil price reaches USD 120/bbl, PHEVs with a pure electric range between 30 km and 50 km would also come close to a zero incremental lifetime cost, once fuel savings are accounted for and if the analysis is undertaken from a societal perspective.

These results illustrate that a 50% improvement of fuel economy (expressed in Lge/100 km) can be achieved at low or even negative social costs thanks to the combination of technological solutions that start from advanced ICEs and range up to ICE-HEVs. PHEVs would also be suitable to reach this level of improvement, in particular if they are conceived as incremental evolutions of hybrids and if they are first offered with relatively low pure electric range. Other options, such as low-range, lightweight EVs serving urban driving, could also fit in this category, especially when the power generation mix is characterised by low emission factors.

As a result, the fuel consumption of new LDVs could be halved in the near-to-medium term at low or possibly negative average cost to consumers, taking account of the value of fuel savings. This would dramatically cut CO₂ emissions and help improve energy security.

These implications have been taken up by the Global Fuel Economy Initiative, launched in March 2009 by the IEA and three partner agencies (see Chapter 4, Box 4.2 for more details).

Implications of the analysis for non-OECD countries

The analysis presented has been calibrated on average LDVs in OECD countries. These are the markets where most of the incremental improvements began to be deployed in the past, and where future deployment may still be led given the greater average income of consumers compared to those in most non-OECD countries.

The global LDV fleet, however, is very diverse, ranging from small city LDVs to large SUV and pick-up trucks. Additionally, region-specific characteristics affect vehicle features, including the set of technologies being used (also with respect to pollutant emissions), the average size of the LDVs being offered and being purchased, and vehicle costs.

LDVs in many developing regions are generally smaller than in OECD markets, with the main exception of some countries where fuel is heavily subsidised or where only the rich own vehicles (and where the share of large vehicles such as SUVs is quite high). In general, there appears to be a lag time for technologies to enter non-OECD markets. In many cases, new vehicles are now being equipped with technologies that entered OECD markets five to ten years ago. In some cases, the presence of an important share of second-hand LDV imports has strengthened this effect.

However, the fast growth of the vehicle market that has been observed in some developing regions began recently to change this picture. Some vehicle models, equipped with advanced technologies, are appearing at nearly the same time in fast-growing markets such as China as they appear in the OECD. Some models are sold worldwide with similar specifications, varying only as needed to meet regulatory requirements and perhaps with different shares for various options (such as engine size or trim level). The global LDV industry is consolidating both in terms of producers and markets.

Where differences do exist, the most important in terms of fuel economy may be vehicle size and price. Small, inexpensive LDVs may not provide much opportunity for deploying new, relatively expensive technologies, and are less likely to be

suitable for advanced technological solutions than large vehicles, especially if such solutions lead to up-front cost increases. With recent high oil prices and the economic downturn, an increased interest in small vehicles has emerged, even in OECD markets, possibly slowing the rate of new technology penetration.

Small LDVs, however, could also represent an interesting option to foster certain advanced technologies. One area is vehicle electrification, since smaller, lighter, more efficient vehicles need fewer batteries to go a given distance than larger vehicles. It is expected that most early introductions of pure EVs will occur in small LDV market segments. The fact that small LDVs tend to be used for urban, relatively short-range driving, is another advantage when it comes to EV introduction. As a result, countries in which small LDV sales dominate may find it relatively viable to introduce large numbers of EVs in the near to medium term.

The overall effect of small vehicles on the total transport energy demand, however, is not easy to assess. On the one hand, small vehicles can contribute to the reduction of fuel consumption in OECD countries. On the other hand, very low-cost small LDVs, such as the Tata Nano and other planned introductions of this type may accelerate motorisation rates in rapidly developing regions. Therefore, while increased sales of smaller vehicles are likely to result in net energy savings in regions such as North America, in regions such as India and China the increased availability of small, inexpensive LDVs may result in increased travel and fuel use.

The introduction of small, inexpensive vehicles may also have a long-term effect on average vehicle sizes and the way vehicles are used. A major deployment of small LDVs could delay a switch towards larger and heavier vehicles that is generally associated with the increase in personal income. If combined with appropriate urban planning policies, small vehicles may fit well with a strategy towards a more environmentally friendly urban structure. In one configuration, a large share of urban travel could be provided by public transport and non-motorised transport, while small individual vehicles could serve the purpose of urban trips not served by public transport. Use of EVs would help to ensure that urban areas receive very little pollutant emissions from the transport system as a whole.

Chapter 4 LIGHT-DUTY VEHICLE EFFICIENCY: POLICIES AND MEASURES

Key findings

- ▶ Most OECD governments and some non-OECD governments have introduced a range of policies to promote LDV efficiency, energy savings and CO₂ reductions. These include voluntary and mandatory efficiency targets, fuel and vehicle tax systems, promoting eco-driving, and promoting the improved efficiency of vehicle components such as tyres. There remains a potential for many countries to benefit from implementing stronger and more comprehensive policy systems.
- ▶ If energy consumption and GHG emissions from personal LDVs are to be limited, consumers need to be encouraged to purchase more efficient vehicles and to reduce their share of travel on personal vehicles. Fuel taxes can provide incremental incentives in this respect, especially if they rise faster than incomes. But many countries currently apply low fuel taxation rates or even outright fuel subsidies, which is very counterproductive. Fuel taxes can provide revenues to pay for infrastructure costs and can be instrumental to provide funding aimed to the development of sustainable transport, such as mass transit systems. They should also cover all the external costs generated by the use of road vehicles (including GHG emissions). CO₂ taxes aimed only at the compensation of GHG-related externalities would result in a relatively low charge to the retail price of motor fuels. For example, a USD 50/t CO₂ tax on gasoline yields only a USD 0.12/L change in price.
- ▶ Vehicle taxes should also be differentiated according to vehicle efficiencies (or CO₂ emissions), in order to incentivise consumers to purchase more efficient vehicles. The total average taxation on vehicles can also influence the motorisation level, since motorisation is more contained (at a given income per capita) in countries imposing higher taxation on the vehicle purchase. Vehicle taxes can also vary depending on vehicle impacts with respect to non-GHG externalities such as pollutant emissions.
- ▶ A large share of LDV fuel savings in the past, and the potential for the future, comes from deploying fuel efficient vehicle technologies. A review of fuel economy policies in selected countries and regions shows that implementation of progressively tighter mandatory fuel efficiency standards for LDVs has proven instrumental in achieving steady, rapid technology uptake while avoiding increases in vehicle size, weight and power, all of which erode the fuel savings provided by the technologies.
- ▶ Efficiency standards typically require achieving a minimum level of fuel efficiency per vehicle or as an average across a particular class of vehicles. When implementing mandatory standards, they should be set in a manner that pushes the market toward efficiency without compromising cost-effectiveness or fairness. This can be challenging, and depends on the level and stringency of targets, and on the design

of standards. Standards should be broad enough to cover all LDVs and should avoid “leakage” of vehicles into categories not covered by the standard. In addition, unless there are clear reasons for not doing so, requirements should be based on reaching a targeted fuel efficiency performance level and not based on promoting particular technologies.

- ▶ The effectiveness of the vehicle efficiency test procedure is an important element in designing standards. Good test procedures reflect as many factors that affect the on-road experience of fuel efficiency as possible. At the same time, they should be the same as or close to local pollutant emission procedures in order to lower the cost of testing vehicles. In addition, since vehicle manufacturers operate in a global market, the greater alignment of test procedures across countries would reduce compliance costs for manufacturers. The international harmonisation activities in UNECE/WP29 (Working Party 29 of the World Forum for the Harmonisation of Vehicle Regulations) can play an important role in this regard, provided it can deliver a concrete and meaningful result within a realistic time frame and provided the resulting testing approach is sufficiently close to the actual driving conditions in different world regions. The harmonisation should account for the relevance of regional differences. It should aim to the reliance on a single methodology that modulates targets taking into account physical parameters such as the vehicle weight or size.
- ▶ Fuel economy labelling and financial incentives at the point of vehicle purchase, such as vehicle taxes and rebates differentiated by fuel economy or CO₂ emissions, can complement standards. By influencing the sales mix of different types of vehicles, they can help avoid a drift toward larger, heavier vehicles that might occur with attribute-based standards while helping industry to market fuel efficient vehicles. Financial incentives can also be designed to balance the impacts on other factors that have a trade-off relationship with fuel efficiency performance.

Introduction

As shown in the IEA Energy Technology Perspectives 2008, ETP 2008 (IEA, 2008a) fuel economy improvements can make an important contribution to the reduction of CO₂ emissions from the transport sector as part of a wider effort to halve overall worldwide emissions by 2050. As described in Chapter 3, improvements in fuel economy could cost-effectively halve the amount of fuel per kilometre used by new LDVs by 2030. If this was achieved, it would save about 0.5 Mtoe of fuel and around 1 Gt of CO₂ per year. These annual savings would continue to increase after 2030 as new vehicles continue to improve and older vehicles are phased out.

Achieving such an outcome should be possible, but it will require strong policies that maximise technology uptake and minimise changes in vehicle attributes such as increases in weight and power that reduce efficiency. Vehicle components not covered in fuel economy tests, traffic flow improvement and eco-driving also need to be addressed in detail, since they are all elements of an integrated approach that is best suited to tackle the topic, as clearly shown in the equations below:

$$\text{CO}_2 \text{ emissions} \left(\frac{\text{g CO}_2 \text{ eq}}{\text{vehicle}} \right) = \text{PN - road fuel economy} \left(\frac{\text{L}}{\text{km}} \right) \times \text{CO}_2 \text{ emission factor} \left(\frac{\text{g CO}_2 \text{ eq}}{\text{L}} \right) \times \text{Vehicle travel} \left(\frac{\text{km}}{\text{vehicle}} \right)$$

$$\text{CO}_2 \text{ emissions} \left(\frac{\text{g CO}_2 \text{ eq}}{\text{vehicle}} \right) = \left(\text{Tested fuel economy} \left(\frac{\text{L}}{\text{km}} \right) \times \text{On - road gap factor} [\%] \right) \times \text{CO}_2 \text{ emission factor} \left(\frac{\text{g CO}_2 \text{ eq}}{\text{L}} \right) \times \text{Vehicle travel} \left(\frac{\text{km}}{\text{vehicle}} \right)$$

The combination of efforts for reducing GHG emissions from the road transport sector involves automakers, fuel providers, governments, and vehicle owners. Automakers are particularly affected by policies to improve tested fuel economy; the fuel industry by policies to reduce carbon content in fuels and other fuel quality aspects; vehicle owners by policies encouraging more efficient use of vehicles. National governments are typically in charge of all regulatory aspects, including those related to fuel economy, fuel quality and taxation. Local governments may be responsible for traffic flow improvements, urban planning and the development of mass transit.

The analysis presented here first reviews the effectiveness of a range of policy measures addressing improvements in the fuel economy of LDVs resulting from tests that have been taken by the European Union, Japan, the United States, China, Korea and Australia. In the following section, the analysis addresses in particular the on-road fuel efficiency, including issues such as the efficiency of vehicle components not covered in fuel economy tests, eco-driving and the use of intelligent transportation systems to reduce congestion.

Box 4.1 ► **IEA, the G8, and efficiency policy**

At their 2005 Summit in Gleneagles in the United Kingdom, G8 leaders agreed to the G8 Gleneagles Plan of Action (GPOA), which identifies a range of actions necessary to mitigate climate change and promote the use of clean energy sources. Among other actions, the GPOA commits the G8 leaders to steps to encourage the development of cleaner, more efficient vehicles. To help this, the G8 leaders asked the IEA to review existing policies and measures for road vehicle efficiency and to identify steps that could be taken to reduce energy use.

Since 2005, the IEA has been engaged in a programme of work in response to this request. This includes an analysis of existing standards and best practices in reducing vehicle fuel use.

The results of this analysis inform relevant parts of this and other chapters of this publication. They also informed the IEA submission to the Hokkaido G8 Meeting in July 2008, at which the IEA recommended 25 different efficiency measures (IEA, 2008b) including mandatory fuel economy standards for LDVs and trucks, standards for tyres, and the use of other measures to promote fuel economy such as incentives to encourage drivers to drive more economically. The following four transport-related efficiency recommendations were among the 25 recommendations.

Recommendation 1: In all countries, appropriate mandatory fuel-efficiency standards are needed for LDVs if significant transport-sector energy savings are to be achieved. Governments should:

- Introduce new mandatory fuel-efficiency standards for light-duty vehicles if they do not already exist, or where they do exist, make those standards more stringent.
- Announce the more stringent content of the proposed standards as soon as possible.
- Harmonise, where appropriate, as many aspects of the future standards as possible.

Recommendation 2: Heavy-duty vehicles account for 30% of worldwide transport fuel use (see Chapter 6). While the industry has already improved heavy-duty vehicle efficiency significantly, large potential remains for further improvements. For heavy-duty vehicles, governments should introduce:

- Fuel-efficiency standards.
- Related policies including labelling and financial incentives based on the vehicle's fuel efficiency.

Recommendation 3: There is a strong need for measures that promote efficient vehicle accessories such as headlights, internal lighting, air-conditioning systems and tyres, which are generally not well covered by current regulatory systems. The IEA has held workshops and conducted analysis on a number of such technologies. IEA findings notably conclude that fuel-efficient tyres and adequate tyre maintenance can reduce vehicle fuel consumption by as much as 5% and that international best practice regarding fuel-efficient tyres involves two components.

- Maximum allowable levels of rolling resistance for major categories of tyre.
- Measures to promote adequate levels of tyre inflation.

Therefore, governments should: a) adopt new international test procedures for road-vehicle tyres measuring the rolling resistance of tyres, with a view to establishing labelling, and possibly maximum rolling resistance limits where appropriate; and b) adopt measures to promote proper inflation levels of tyres; this should include governments, acting in co-operation with international organisations including UNECE, making mandatory the fitting of tyre-pressure monitoring systems on new road vehicles.

Recommendation 4: Smart, safe driving techniques can lead to significant fuel savings. In several countries, eco-driving has become an integral part of transport sector emissions reduction strategies. In many other countries, however, eco-driving remains on the margins of transport policy development. Therefore, governments should ensure that eco-driving is a central component of government initiatives to improve energy efficiency and reduce CO₂ emissions. Government support for eco-driving should include promotion of driver training and deployment of in-car feedback instruments.

The four recommendations, if implemented globally, could save as much as 1.6 Gt CO₂ per year by 2030. The G8 leaders, in the Summit document, declared that they “will maximise implementation of the IEA’s 25 recommendations on energy efficiency”. Moreover, recognising the contribution that energy efficiency could make to higher economic performance, higher energy security and reducing climate change, it was urged that these recommendations should be implemented worldwide as soon as possible.

Overview of fuel economy policies

The most common measures to improve technical fuel efficiency are:

- regulatory standards;
- voluntary targets;
- financial incentives; and
- improved consumer information.

Most countries rely on a combination of these four measures to fulfil their policy aims. Table 4.1 outlines a range of national approaches to establishing mandatory and voluntary fuel efficiency measures. All of the countries reviewed also have a range of policies that provide financial incentives and promote consumer awareness through labelling systems or other approaches.

Table 4.1 ► Status of measures for LDV fuel efficiency improvement

	Regulatory standards	Voluntary targets	Key Dates	
			Year set	Target year or final year covered
EU		IM	1998	2012
	IM		2008	2012 / 2015
	PL		2008	2020
Japan	IM		1999	2010
	IM		2006	2015
US	IM		1975	1985
	IM		2007	2020
	PL		2009	2016
Canada		IM	1976	2010
	PL		2008	2011/2020
China	IM		2004	2005
	IM		2004	2008
	PL		2009	2012/2015
Korea	IM		2005	2006
	PL		2005	2012/2015
Australia		IM	1978	1987
		IM	1987	2000
		IM	2005	2009

Notes: IM: implemented; PL: planned or under consideration; Voluntary and Regulatory measures in EU are based on reducing CO₂ emissions not directly on fuel efficiency; those in Canada are based on reducing GHG emissions. US CAFE standards for trucks have been updated several times between 1985 and 2009.

The United States, Japan, China, Korea and the European Union regulate the fuel efficiency of LDVs through mandatory standards. The United States has the longest history of mandatory fuel efficiency standards, having introduced them in the

mid-1970s. In 1998, Japan adopted the Top Runner standards. These require that each new generation of vehicles must, at least, meet the fuel efficiency level of the current most efficient vehicles. China introduced regulatory standards for passenger cars in 2004, Korea in 2005 and the European Union in 2008.

Until recently, the European Union operated to a set of voluntary targets agreed with industry associations in 1998. But in December 2008, the European Union introduced a requirement on manufacturers to reduce CO₂ emissions from cars that will be fully effective by 2015. Canada and Australia currently have voluntary programmes for the promotion of vehicle fuel efficiency but are moving towards regulatory programmes. In November 2007, legislation was put in place to enhance the Canadian federal government's authority to regulate vehicle fuel efficiency, which will enable regulations to be brought into effect for the 2011 model year. Additionally, the Government of Canada announced in April 2009 that it will develop regulations under the Canadian Environmental Protection Act, 1999 in order to regulate also CO₂ emissions from new cars and light trucks, to take effect beginning with the 2011 model year. The Australian government reached an agreement with industry in 2003 on a set of voluntary targets. However, in the past these have not been complied with.

The United States, Japan, China and some EU countries also have in place vehicle tax incentive programmes. In Japan, buyers of fuel efficient and less polluting vehicles are eligible to receive a tax deduction, while in the United States, drivers of fuel inefficient vehicles pay an additional tax levy. China recently implemented a variable vehicle purchase tax regime in which vehicles with high CO₂ emissions are charged a much higher levy than fuel efficient vehicles. Vehicle-based tax systems based on CO₂ emissions are becoming common in countries within the European Union, but approaches vary significantly.

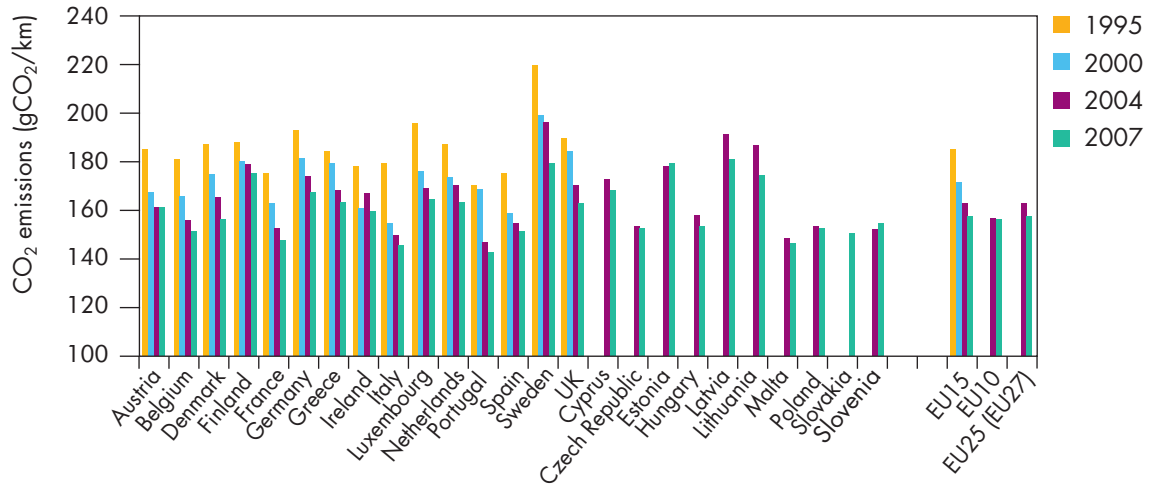
The European Union

In the European Union, fuel efficiencies improved steadily until the mid-1980s, at which point average fuel efficiency remained the same until the mid-1990s. In the mid-late 1990s, the European Commission, working with the European, Japanese and Korean automobile manufacturers' associations, set voluntary commitments to achieve progressively tighter CO₂ emissions targets (EC, 1999a). These targets were designed such that through technological adjustments, the average emissions of all new cars sold in the European Union would be no more than 140 g CO₂/km by 2008 and through non-technological measures (taxation and labelling) would reach 120 g CO₂/km by 2012.

Between 1995 and 2005, the voluntary agreement in the European Union helped to achieve impressive reductions in fuel consumption per kilometre in new European LDVs (Figure 4.1). But these improvements began to slow in many countries after 2004.

The 2009 European regulation is setting emission performance standards for new passenger cars as part of the EU's integrated approach to reduce CO₂ emissions from LDVs to reach 120 g CO₂/km. By 2015, manufacturers are required to reduce average emissions from all new passenger vehicles registered in the European

Figure 4.1 ▶ Average specific CO₂ emissions of new passenger cars in the EU Member States in 1995, 2000, 2004 and 2007



Source: European Commission (2007a), Ademe (2009).

Key point

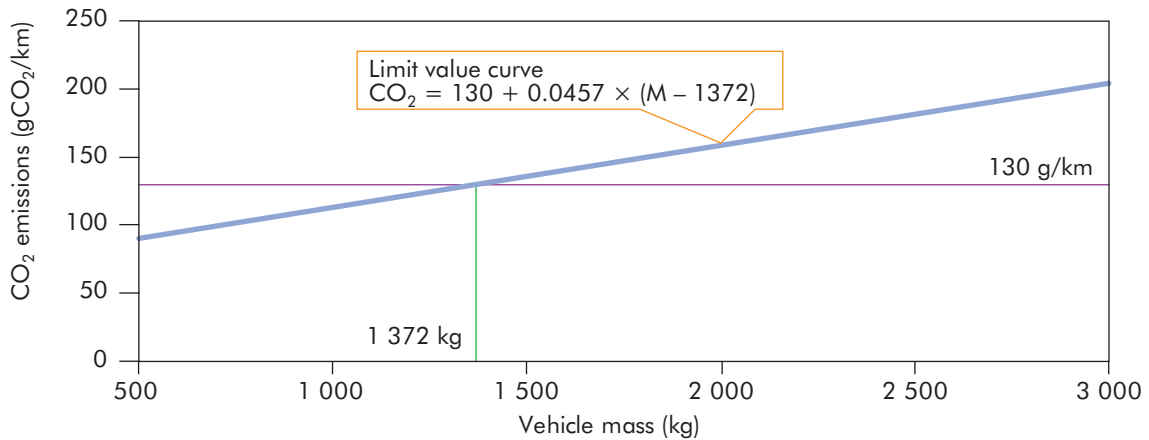
Average new passenger car CO₂ emissions declined in all EU countries between 1995 and 2007, though the decline has slowed in recent years.

Union below 130 g CO₂/km. Complementary measures, such as efficiency improvements in car components and a gradual reduction in the carbon content of road fuels, are required to contribute a further emissions cut of up to 10 g CO₂/km, thereby reducing overall average emissions to 120 g CO₂/km (EC, 2009a).

The legislation sets a limit value curve defining the maximum permitted CO₂ emissions for new passenger cars according to their mass (Figure 4.2). The curve is set in such a way that a fleet average for all new passenger cars of 130g CO₂/km is achieved. The target function was also set to dissuade manufacturers to increase weight. From 2012, manufacturers will be required to ensure that the average emissions of all the new passenger cars registered in the European Union are below the permitted maxima. In 2012, 65% of each manufacturer's newly registered passenger cars must comply on average with the limit value curve. This will rise to 75% in 2013, 80% in 2014, and 100% from 2015 onwards.

The legislation is designed to incentivise manufacturers to comply by imposing an excess emissions premium on those whose average emission levels are above the limit value curve. This premium is based on the number of grams per kilometre (g/km) that the average passenger car registered by the manufacturer is above the curve, multiplied by the number of passenger cars registered by the manufacturer. Depending on the year and the level of excess, this premium ranges up to EUR 95 per g CO₂/km.

In the adopted legislation on CO₂ from passenger cars, a long-term target of 95 g CO₂/km is specified for the year 2020. The modalities for reaching this target and the aspects of its implementation, including the excess emissions premium, will have to be defined in a review to be completed no later than the beginning of 2013.

Figure 4.2 ▶ Limit value curve of the EU regulation

Source: European Commission (2007a).

Key point

Under the European Commission's limit value curve regulation new passenger vehicle CO₂ emission limits are set higher for heavier vehicles.

Separately, in August 2008, the European Commission issued a concept paper for reducing CO₂ emissions from light commercial vehicles (EC, 2008c). This proposes a requirement to reduce CO₂ emissions to 175 g CO₂/km by 2012 and 160 g CO₂/km by 2015. A full regulatory proposal by the European Commission is expected in 2009.

Efficiency policies within the European Union

EU directive 1999/94/EC adopted in 1999 directs EU countries to require information on fuel economy and CO₂ emissions to be displayed on all new LDVs being sold. This enables vehicle purchasers to make an informed choice between alternatives (EC, 1999b).

Different EU Member States have adopted different approaches. Systems typically use a threshold system in which cars within a certain range of grams of CO₂/km above or below specified threshold values are given a letter rating. But the energy and CO₂ performance thresholds are not harmonised across the European Union. The European Commission has indicated that it plans to propose an amendment to the EU labelling directive 1999/94/EC by the end of 2009 with a view to increasingly aligning labelling systems (EC, 2009d).

EU Member States are responsible for implementing and collecting taxes. In recent years, a number of Member States have introduced vehicle taxes designed to encourage lower CO₂ emissions. Table 4.2 shows EU countries that have fiscal measures based on vehicle CO₂ emission rates, either at time of purchase or to be paid annually. Rates are shown for two mid-sized cars, one emitting 120 g CO₂/km, the other 150 g CO₂/km. The range is quite broad in both absolute tax levels and the difference in taxes between the vehicle types.

Table 4.2 ► Comparison of CO₂-based fiscal measures on car acquisition and ownership in selected European countries (Based on a mid-size car, EUR 12 000 pre-tax purchase price – 1800cc gasoline engine – 4m long)

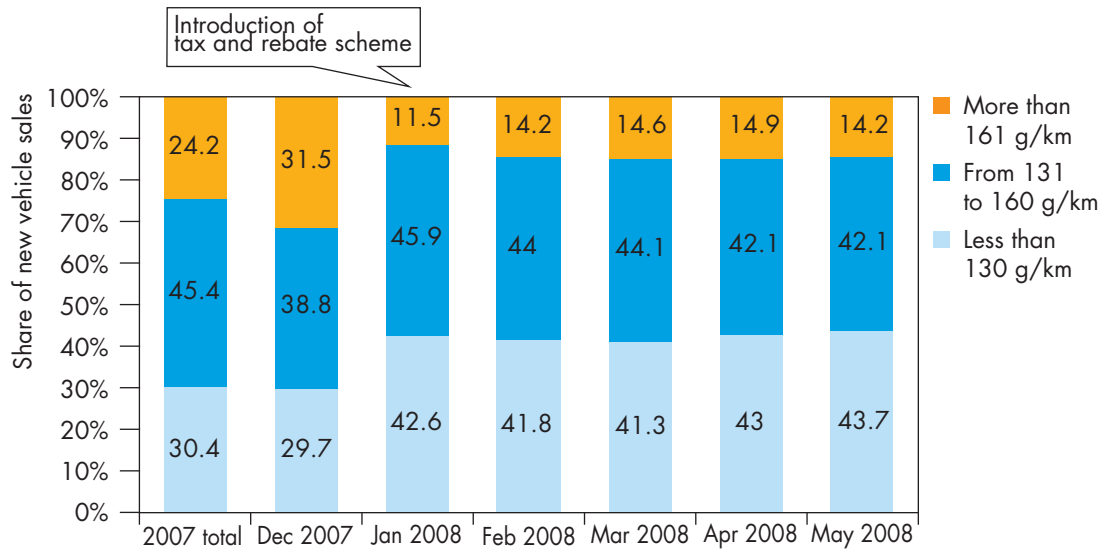
	mid-size car, 12 000 pre-tax purchase price 1800cc gasoline engine - 4m long (Euros)					
	Case 1: 150 g CO ₂ /km		Case 2: 120 g CO ₂ /km		Difference between the two vehicles	
	Acquisition	Ownership	Acquisition	Ownership	Acquisition	Ownership
Austria	0		-300		300	
Belgium	0		0		0	
Cyprus	380	14	331	12	49	12
Finland	2 782		2 342		440	
France	0	0	-700	0	700	
Germany		300		0		300
Ireland	2 400	302	1 680	104	720	198
Luxembourg		99		58	41	
Malta	5 028	140	3 408	110	1 620	30
Portugal	4 001	201	3 023	173	978	28
Spain	570		0		570	
Sweden		240		200		40
The Netherlands	2 236		2 036		200	
United Kingdom		140		40		100

Note: empty cell means no tax on acquisition / ownership, for all vehicles ; zero means, for the particular vehicles considered in this table, no tax price for acquisition / ownership.

Source: Based on ACEA (2009a).

France reformed its vehicle registration tax scheme near the end of 2007. The scheme uses a combination of vehicle taxes and rebates geared to CO₂ emission levels with large differentials for vehicles in different CO₂/km categories. The scheme includes a plan to lower the thresholds every two years. Almost immediately after the system was introduced, sales of high CO₂ emitting vehicles in France dropped significantly, while sales of low CO₂ emitting vehicles increased (Figure 4.3).

Sweden implemented a CO₂-based annual road tax scheme in 2005. This imposes an additional level of annual tax for every gram of CO₂ emitted by a vehicle in excess of 100 g/km. From 2011, vehicles that emit less than 120 g/km will be exempt from annual tax, and other vehicles will pay a higher level of tax per gram above 120 g/km. For diesel vehicles, Sweden's financial incentive scheme also incentivises lower emissions of particulates (SRA, 2009).

Figure 4.3 ▶ Vehicle sales by CO₂ emission categories in France, 2007-2008

Source: CCFA, 2009.

Key point

Passage of CO₂ based vehicle registration tax with a planned phase-in period led to immediate shift in vehicles purchases toward lower CO₂-intensive vehicles.

Germany introduced a CO₂-based annual road tax scheme in July 2009. The scheme is based on a combination of engine size and CO₂ emissions. Gasoline vehicles are taxed per 100 cm³ of engine displacement and for every gram of CO₂ in excess of 120 g CO₂/km. Diesel vehicles are taxed at a much higher rate per 100 cm³ of engine displacement and the same rate as gasoline vehicles for every gram of CO₂ in excess of 120 g CO₂/km. The reference limit for the emissions component of the tax will be reduced from 120 g CO₂/km to 110 g CO₂/km in 2012 and to 95 g CO₂/km in 2014 (BMF, 2009).

Japan

The Japanese government's approach is based on fuel efficiency targets (as distinct from CO₂ emission targets) set by reference to Top Runner standards. These standards are based on the best performing vehicles in the national market and on a range of other factors.

Fuel efficiency standards using the Top Runner method were first introduced in 1999. These set efficiency levels to be reached by gasoline and diesel powered LDVs by 2010. They were followed by standards for other vehicle types, such as LPG vehicles in 2003 and for trucks in 2006, with penalties that take effect in 2010 and 2015, respectively. The truck standards are the first to cover this type of vehicle anywhere in the world. The resulting system of regulation covers virtually all types of road vehicle in the country (MLIT, 2007c).

In 2007, the government published updated Top Runner fuel efficiency standards for LDVs to reach in 2015. These are based on establishing the most fuel efficient vehicles in each of 16 different weight classes. The performance of these vehicles is used as a target fuel efficiency level that must be met by an average of all cars sold by a manufacturer within a given weight class. These standards are shown in Table 4.3.

Table 4.3 ► 2015 Japanese Top Runner standards for passenger vehicles

Class	Vehicle weight (kg)	Target standard value (km/L)
1	0 - 600	22.5
2	601 - 740	21.8
3	741 - 855	21.0
4	856 - 970	20.8
5	971 - 1 080	20.5
6	1 081 - 1 195	18.7
7	1 196 - 1 310	17.2
8	1 311 - 1 420	15.8
9	1 421 - 1 530	14.4
10	1 531 - 1 650	13.2
11	1 651 - 1 760	12.2
12	1 761 - 1 870	11.1
13	1 871 - 1 990	10.2
14	1 991 - 2 100	9.4
15	2 101 - 2 270	8.7
16	2 271 +	7.4

Note: The law in Japan also requires manufacturers to provide information on the fuel efficiency of new vehicles through labelling. CO₂ emission values are also shown, converted from the fuel efficiency values.

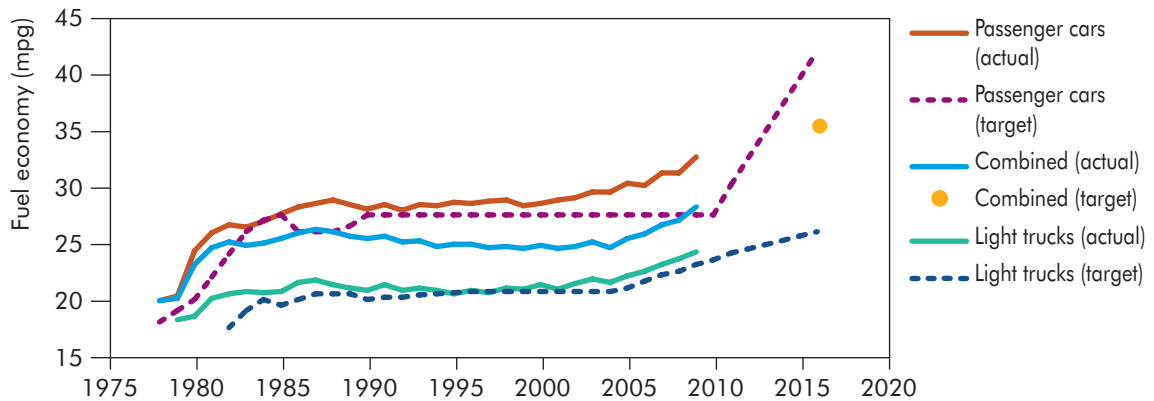
In April 2004, a vehicle fuel efficiency certification programme was implemented in order to further stimulate consumer interest in fuel efficiency and to encourage the sale of more fuel efficient vehicles. Under the programme, vehicles are ranked according to their fuel efficiency performance and certified in four levels – those that meet the Top Runner standard for the relevant class and those that beat it by 5%, 10% or 20%. Manufacturers can attach stickers showing the vehicle's certified fuel efficiency performance level to the rear windows of their vehicles.

The United States

In the United States, vehicle fuel economy has been regulated since 1975 under the Corporate Average Fuel Economy (CAFE) programme. Under CAFE, new cars and

light trucks up to 8 000 pounds (about 3 600 kg) are required to meet a minimum fuel economy target based on miles per gallon (MPG). Separate standards exist for cars and light trucks. The standards have been in force at approximately the same levels originally set in the mid-1980s, although in recent years the standard for light trucks has been strengthened. For cars, the standard can only be changed by Congressional legislation but for light trucks, the United States Department of Transportation (US DOT) has the authority to set higher or lower standards. CAFE standards up to model year 2016 are shown in Figure 4.4.

Figure 4.4 ► United States CAFE standards



Note: 2016 targets were proposed by the United States President in May 2009, but are not yet law.

Source: NHTSA, 2009a ; White House Press Office, 2009.

Key point

Steady regulation limit proved inefficient, as higher light trucks share made the average fleet fuel economy decrease. High oil prices have triggered recent improvements.

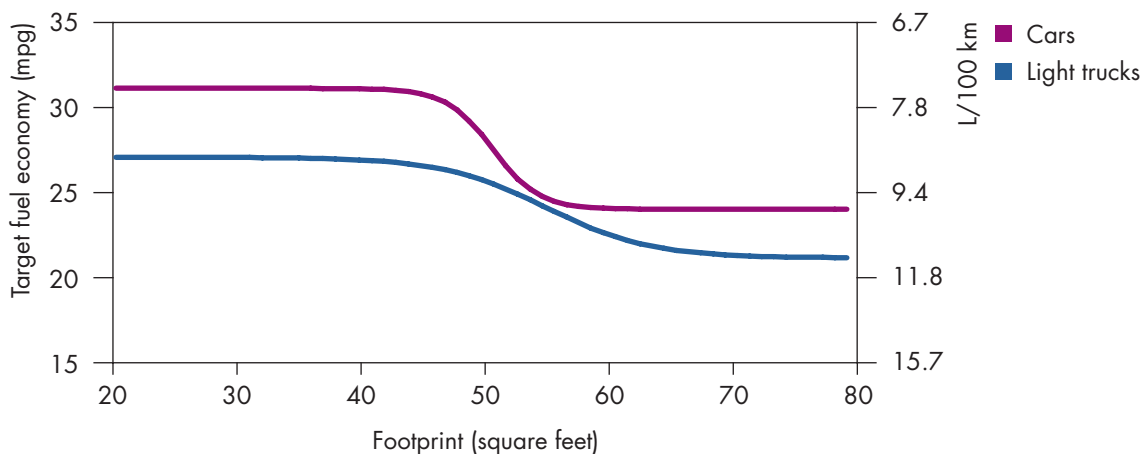
In the United States, window labels have provided information on fuel economy estimates for more than 30 years as a means of helping shoppers to compare different vehicles. The labelling includes information showing the fuel consumption of the vehicle, its position in the relevant class of vehicles, its expected on-road fuel efficiency and an estimate of the annual fuel cost. The window sticker programme uses a fuel economy estimate calculated by the US Environmental Protection Agency (US EPA) to take account of the estimated gap between tested efficiency and actual on-road efficiency (EPA, 2006a). The results vary by vehicle, but on-road efficiency levels are typically 15% to 20% lower in terms of MPG than the official CAFE test results.

In April 2006, the US DOT published a rule reforming the structure of the CAFE programme for light trucks in an effort to balance fuel efficiency and safety goals. The rule introduced an attribute-based approach for setting CAFE standards for model years 2008 to 2011 (NHTSA, 2006c). In December 2007, Congress enacted the Energy Independence and Security Act (EISA, 2007), which extended the attribute-based approach to passenger vehicles and applied CAFE standards to all four-wheeled vehicles with gross vehicle weight rating (GVWR) under 10 000 pounds (4 535 kg), with the exception of medium-duty, non-passenger work trucks

and vans. In 2009, the Obama Administration set a final standard for model year 2011 and directed the US DOT and the US EPA to develop joint fuel economy and CO₂ emission standards for LDVs for model years 2012 to 2016 (NHTSA, 2009; NHTSA and EPA, 2009). The Obama Administration also proposed implementing the CAFE standards four years earlier, *i.e.* 2016 instead of 2020 (Figure 4.4).

Under the reformed CAFE system, a manufacturer is required to achieve a sales-weighted average fuel economy target based on the mix of vehicles sold by vehicle footprint. The vehicle's footprint is defined as the average track width multiplied by the wheelbase. Each vehicle with a unique footprint is assigned a target fuel economy, specific to the footprint value shown in Figure 4.5. Passenger vehicles and light trucks are still regulated separately but adhere to the same compliance methodology. Targets for 2012 to 2016 are expected to be set by early 2010.

Figure 4.5 ► Reformed CAFE targets for model year 2011



Source: NHTSA, 2009b.

Key point

The curves for light trucks and passenger cars are different in shape and range, to accommodate market demand.

Since 1978, the United States has also had a national vehicle tax system, known as the gas guzzler tax. The tax applies only to passenger cars achieving less than 22.5 MPG (equivalent to more than 10.5 L/100 km). Light trucks, including minivans and SUVs, are not covered. In recent years, the tax has applied only to a very small share of vehicle models or sales.

China

China introduced fuel efficiency standards for passenger vehicles in 2005, with the goal of slowing fuel import growth and improving technology transfers to the domestic Chinese auto-manufacturing industry. The standards have been updated several times to increase uniformity and encourage smaller and more fuel-efficient vehicles. The system is composed of an engine displacement excise tax (*i.e.* sales

tax) and minimum urban fuel economy standards for 16 vehicle weight categories. The Chinese system includes SUVs as passenger vehicles. Updated excise tax rates took effect 1 January 2009, and range from 1% for small engines to 40% for the largest engines. Because the fuel economy standards are based on urban driving and not highway driving, they are not directly comparable to United States CAFE standards. The International Council on Clean Transportation (ICCT) estimates that the average new passenger vehicle in China achieve 8 L/100 km in 2008 and will achieve 6.5 L/100 km in 2015.

Republic of Korea

The Korean Presidential Committee on Green Growth announced early July 2009 that the average CO₂ emissions of new vehicles should reach 140 g CO₂/km by 2015. In 2007, the average CO₂ emissions of new vehicles reached 201 g CO₂/km. This is the most ambitious fuel efficiency policy to date with a decrease of 4.4% from 2007 to 2015. Fiscal measures on both manufacturers and consumers are planned to reach the target. At the time of printing, no details were available regarding how this system will be implemented (JoongAng Daily, 2009).

Box 4.2 ► **The Global Fuel Economy Initiative and 50-by-50 campaign**

As shown in Chapter 3 and highlighted in Box 3.2, the IEA estimates that if strong enough measures were implemented globally, the fuel consumption of new LDVs could be halved by about 2030 at low or possibly negative cost to consumers, taking account of the value of fuel savings. This would dramatically cut CO₂ emissions and help improve energy security.

In March 2009, the IEA and three partner agencies – the International Transport Forum, the United Nations Environment Programme (UNEP) and the FIA Foundation – launched the Global Fuel Economy Initiative (GFEI). The overall objective of this Initiative is to make all LDVs worldwide 50% more fuel efficient by 2050 than average efficiencies in 2005. The Initiative seeks to achieve this primarily by improving international understanding of the potential for greater fuel economy and the cost of achieving it, and by providing guidance and support in the development of policies to promote fuel efficient vehicles. The Initiative's activities include:

- *Developing improved data and analysis on fuel economy around the world; monitoring trends and progress over time; and assessing the potential for improvement.*
- *Working with governments to develop policies that encourage greater fuel economy in the vehicles produced or sold in their countries; and helping make policies more consistent across countries so as to lower the cost and maximise the benefits of improving vehicle fuel economy.*
- *Working with stakeholders, including car manufacturers, to better understand the potential for fuel economy improvement and soliciting their input and support in working towards improved fuel economy.*
- *Supporting regional awareness initiatives to provide consumers and decision makers with the information they need to make informed choices.*

The Initiative will issue reports from time to time. It will also support the development of vehicle testing and consumer information systems in regions where these are not yet available.

More information on the Initiative is available at: www.50by50campaign.org.

General considerations in designing fuel economy policies

The fact that different countries and regions have different policies for improving the technical fuel efficiency of vehicles creates an opportunity for policy makers to consider how those different approaches can lead to different outcomes.

Voluntary and mandatory measures

Voluntary programmes were most popular during the 1980s and 1990s, when many governments hoped that car manufacturers would improve the fuel economy of their products without the need for binding regulation. Until 1999, only the United States had regulatory fuel economy requirements for LDVs. Japan implemented the Top Runner Program in 1999. China, Korea and the European Union brought in regulatory programmes more recently.

Table 4.4 shows the planned targets of different regulatory standard systems, as well as past achieved improvements. Past efforts have achieved varying rates of improvement, but in all cases future targets will require a significantly faster rate of improvement. These rates, if achieved, will result in substantial average fuel economy improvements in these countries through 2015, roughly in line with trends in the BLUE Map scenario and targets identified in the Global Fuel Economy Initiative (GFEI) (Box 4.2). But such rates will be needed worldwide, and well beyond 2015, in order to achieve the GFEI target of a 50% improvement in new LDV efficiency by 2030 relative to 2005 levels.

Regulatory design

The design of various mandatory schemes may have played an important role in determining their overall impact. For example, the level of ambition inherent in schemes may affect the rate, as well as the level, of improvement they achieve. The scope of schemes will affect the types and numbers of vehicles that are brought within the regulations. Regulatory loopholes can allow manufacturers to avoid making the expected improvements.

Figure 4.6 shows the trends in fuel economy and weight for new LDVs in Japan, the European Union and the United States from 1990 to 2003. This shows that, since 1997, the fuel efficiency of new Japanese LDVs has increased very rapidly, with almost no average weight increase. The fuel efficiency of new LDVs in the European Union and in the United States has improved only slowly over the same period, and average vehicle weights have increased. Taking both cars and light trucks together, the fuel efficiency of new LDVs in the United States has decreased and average

Table 4.4 ► Past achievements and future requirements for fuel economy targets

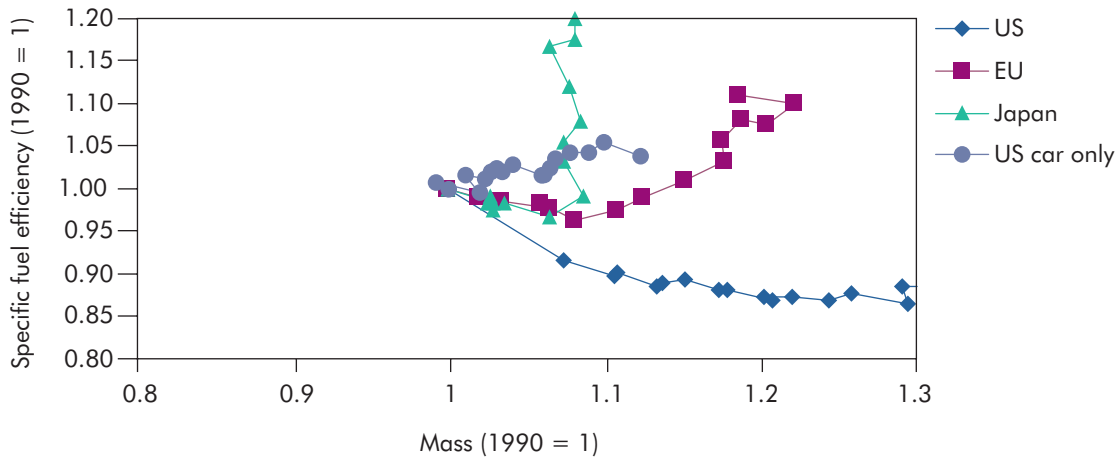
	Years covered by regulations	Standard differentiation	Averaging system	Achieved average annual improvement, 1995-2007 (g CO ₂ /km)	Targets	Required average annual improvement, 2007- target year (g CO ₂ /km)*
US CAFE	1978-2020	Cars and light trucks; vehicle footprint	Manufacturer average within each footprint	0.5% for all LDVs; 0.7% for cars and 0.9% for light trucks	39 mpg by 2016 for passenger cars and 30 mpg by 2016 for light trucks; 35.5 mpg by 2016 for passenger LDVs (announced)	2.6% for all LDVs - 2016
Japan	1985-2015	Differentiation by weight class	Manufacturer averaging within each weight class; trading between classes	1.8%	16.8 km/L by 2015 (JC08 test cycle)	1.9% - 2015
EU	2012-2020	Differentiation by average weight	Manufacturer fleet averaging; trading between manufacturers	1.3%	130 g CO ₂ /km by 2015; 95 g CO ₂ /km by 2020 (announced)	2.2% - 2015
China	2008-2015	Differentiation by weight class	No averaging		Depending on the weight class	
Korea	2012-2015			-1.3%	17 km/L by 2015 (US City cycle, announced)	4.4% - 2015

*: improvement rates based on conversion to CO₂ g/km from each countries own units; some regions have a different base year for improvements: for example, in Japan the revised Top Runner standard, with a base year of 2004, targets a 1.7% improvement per year, 2004-2015. This table shows just the changes required between 2007 and the target year for each region.

Sources: NHTSA, 2009; MKE, 2008; MKE, 2009; MLIT, 2007a; MLIT, 2007b; European Commission, 2009a; European Commission, 2009c, White House Press Office, 2009 and JoongAng Daily, 2009

vehicle weights have increased significantly, largely as a result of the rapid growth in sales of larger, heavier light trucks such as SUVs.

Many factors could have played a role in affecting these different trends, including fuel prices and different levels of income growth in different regions. But a number of features of different regulatory regimes may help explain different outcomes.

Figure 4.6 ► Fuel efficiency and weight evolution, 1990-2006

Source: JAMA.

Key point

Since 1997 LDV fuel efficiency in Japan has increased rapidly with little increase in vehicle weight, while in the U.S. fuel efficiency has fallen and weight has increased.

For example, the Japanese standards and targets have sought to achieve a much steeper rate of improvement than those in the United States and somewhat steeper than those in the European Union. The mandatory nature of the Japanese standards has clearly been a factor since the EU's voluntary targets have not been met even though they were less stringent than those in Japan. In terms of regulatory design, applying lower standards for light trucks than for cars in the United States has permitted light trucks to remain much less fuel efficient than cars, and encouraged design shifts that have resulted in many more light truck models than 20 years ago.

Regulatory scope

The scope of a regulation not only determines what is covered but it also creates an opportunity for gaming, *i.e.* potential incentives to take steps to evade it or to reduce its impact. For example, in respect to tightly specified fuel economy regulation, manufacturers may see an incentive to increase the weight of vehicles so that they either fall outside the scope of the regulation entirely or tip over into a less tightly regulated category. Recognising this, many governments have sought to widen the scope of their fuel efficiency regulations.

Testing procedures

In terms of testing, effective regulations will ensure that the costs of compliance on manufacturers are reasonable and that tests are regarded as being credible by consumers. Fuel efficiency values are generally tested with the same or similar test procedures used to test the other pollutant emissions of vehicles. This is done, in part, because it is an effective way to reduce the cost of testing and, in part, because some technologies for improving fuel efficiency can increase other pollutant emissions.

Some manufacturers – especially those of LDVs – reduce testing costs per vehicle by producing large amounts of the same type of vehicles. Small volume vehicle manufacturers need to find ways to decrease the costs of the testing per vehicle. Some are looking at new methods, such as computer simulation, to help in this respect.

There have also been some efforts to harmonise at least some aspects of testing procedures. This would help to reduce the costs to manufacturers by enabling tests in one regulatory regime to apply in other regulatory regimes. But it is likely to be difficult to achieve, especially in the short term. An internationally harmonised test procedure is currently being discussed in UNECE/WP29. If agreed, this would enable countries around the world to use similar labelling systems and encourage the adoption of similar regulatory systems or at least systems based on similar measurements.

Consumers expect published test fuel consumption figures to be similar to the fuel consumption they experience in actual use on the road. To achieve this, test procedures need to be designed in such a way as to reflect real-life vehicle performance. Such procedures also need, however, to take account of the risk of increasing the cost of testing.

Technology neutrality

Fuel efficiency standards are usually set in terms that require the same level of fuel efficiency regardless of technology. But in some cases, requirements are established on the basis of specific technologies. In general, setting requirements that favour one kind of energy efficiency technology over another tends to distort technology development and may result in inefficiencies. For example, creating special incentives for hybrid vehicles may incentivise the development of vehicles that are nominally hybrid but not necessarily the most fuel efficient, either among possible hybrid designs or even as between hybrid and conventional technologies. Policies designed to encourage very efficient vehicles are more likely to encourage adoption of very efficient hybrid designs, as well as other very efficient designs and technologies.

In some situations, it may be justifiable to promote particular technologies, especially where such technologies need assistance to overcome major barriers. For example, EVs are generally highly fuel efficient (on a tank-to-wheel basis) but they will need to be supported by very substantial investments in infrastructure, e.g. for recharging, and by a co-ordinated approach to make them competitive with alternative, less efficient technologies. There is a risk to governments here, in that EVs may always need regulatory preference and subsidy to be competitive. Governments need to think carefully before committing to technology-specific regulation.

Mechanisms to increase cost effectiveness

Existing regulatory measures use a range of mechanisms to increase cost effectiveness. These include:

- **Manufacturer fleet averaging** – applying standards to a range of vehicles on average, rather than to every model or every model variant.

- **Attribute-based targets** – that apply different targets to different types, sizes or weights of vehicles.
- **Credit trading systems** – allowing manufacturers that beat the standard to sell credits to those who fall short of it.
- **Longer lead times** – giving manufacturers longer advance notice of the application of a specified requirement so that they can plan more effectively to meet it.

Although generally helpful in keeping down regulatory costs, some of these measures can also create perverse incentives or add to regulatory costs. For example, attribute-based standards may encourage manufacturers to change vehicle specifications to move into vehicle categories in which standards are less strict. The United States CAFE system has only two broad categories, for cars and light trucks. The reduction in sales of large cars and the parallel growth in sales of light trucks between 1985 and 2005 suggests that such shifting occurred on a large scale under that system. Although the shifts were clearly driven by consumer demand, the regulatory structure enabled an outcome that was directly opposite that which was originally intended.

The risk of encouraging a behaviour aimed to ease the burden of regulations by changing vehicle specifications is reduced if an adjustment mechanism is built into the legislation so that the assumed average fleet characteristics never stray too far from reality.

This was not incorporated in the CAFE system, while it is included in the EU Regulation on passenger cars through the adjustment of a parameter that can be adapted every three years. Still, a risk similar to the one in CAFE that encouraged the US shift to light trucks exists in the present system of European vehicle classification, where passenger cars and light commercial vehicles (including vans) are regulated separately.

Standard stringency

The more stringent a requirement, the greater the effect it will have on outcomes. But more stringent requirements also increase costs. To maximise economic benefits, targets should be set so that the marginal benefits to society from full compliance equal the marginal costs, though this point may be difficult to determine.

This approach, in part, guides the European Commission and the United States National Highway Transportation Safety Administration (NHTSA) policy aim to set the level of ambition at the point where the increased retail cost of a vehicle is offset by savings from reduced fuel consumption. This point depends on expectations of the cost and the effectiveness of existing and emerging technologies, together with financial considerations such as discount rates and appropriate payback periods. An alternative is to base future standards on the best existing standards, as in the Japanese Top Runner Program.

Different countries impose different standards or targets for future vehicle efficiencies. These are difficult to compare meaningfully, given for example differences in regulatory categories, test procedures and compliance methods.

Some governments set standards to save fuel consumption while others try to curb CO₂ or GHG emissions.

Box 4.3 ► **Comparing fuel economy across regions**

Comparing fuel economy statistics across countries and regions is complicated by a number of factors, including the wide differences in test procedures used.

The definition of the test cycle on which fuel economy estimates are measured can have a significant effect on the apparent fuel consumption of vehicles. For example, hybrid vehicles are generally relatively fuel efficient in congested traffic conditions, whereas diesel vehicles are more efficient than gasoline vehicles, everything else being equal. Vehicles sold in a country tend to be optimised for the use and driving condition in that country.

Japan recently introduced a new test cycle that was expected to result in 10% improvements in fuel efficiency estimates compared to the previous test cycle. In fact, results varied widely for different vehicles, with some showing a 5% improvement and others a 15% improvement. In the United States, the US EPA's new test methods introduced in 2007 were expected to result in urban cycle MPGs dropping by about 12% on average and by as much as 30% for some vehicles. Without standardised fuel cycles, it is difficult to compare meaningfully the fuel economy statistics produced by different countries.

In addition, different countries and regions use different metrics to measure fuel economy. While national differences in the units used can be simplified by applying the appropriate conversion factor, some countries regulate in terms of fuel use and others in terms of CO₂ or GHG emissions for a standard distance travelled. Vehicles with the same CO₂ emissions may demonstrate different levels of fuel efficiency. So, for example, 130 g CO₂/km is equivalent to about 4.7 L/100 km for diesel cars and 5.5 L/100 km for gasoline cars. The State of California regulates several GHGs. As a result, vehicles that emit, for example, high levels of N₂O could be more tightly regulated than other cars, even if they emitted less CO₂ or were more fuel efficient.

UNECE WP-29 has started to develop a harmonised test procedure for LDVs based on a common test cycle. The European Union, Japan, India, China and the United States have committed to provide data for cycle development.

Comparison of the overall and annual outcomes achieved by the EU, US and Japanese approaches to regulation suggests that they all have the ambition to improve fuel efficiency by 2.0% per year or more. This is a more rapid rate of improvement than has occurred in the absence of regulation.

Labelling

Information on the fuel economy of vehicles is essential if consumers are to understand the choices available to them. But an European Commission study (EC, 2005) on the effectiveness of the car labelling directive in EU Member States found that labelling had a relatively small impact on consumer decisions or on the sales of more efficient vehicles. In response, the Commission recommended the elimination

of national schemes. Instead, it proposed that it should run a common EU-wide scheme that would extend the scope of the labelling scheme, introduce common energy efficiency classes, and give consumers an indication of annual running costs. In the United States, a uniform and fairly detailed labelling system has been in place for the past 20 years. During this period, the average fuel efficiency of LDVs has worsened.

In isolation, labelling systems are unlikely to lead to significant fuel efficiency improvements. However, fuel efficiency labels do help consumers compare vehicle choices, and can help consumers understand the tax implications over the lifetime of the vehicle in fiscal regimes that incentivise fuel economy. This is one of the reasons why labelling works best when directly coupled with a differentiated taxation system (as in the United Kingdom).

Financial incentives

Fuel consumption or CO₂-based vehicle tax systems send a direct signal to consumers to encourage them to purchase more efficient vehicles. Consumer demand can be expected to encourage producers to make more efficient vehicles and to improve the efficiency of existing models in order to shift them into lower tax classes. In theory, where manufacturers are regulated to produce specific outcomes, there should be no need to deter consumers from undesirable choices by taxing them. But in practice, experience suggests that taxation regimes can usefully complement regulatory systems.

For example, in a regulatory system with fleet averaging such as CAFE, manufacturers must meet a target as an average across all vehicles they produce. But if competitive pressures result in the associated cost not being passed on to consumers in such a way as to deter them from demanding larger or otherwise less efficient vehicles, it becomes increasingly difficult for manufacturers to meet the standard. A differential tax system can help reinforce consumer demand to make it easier for manufacturers to meet the standard.

A regulatory system such as Top Runner, with many small categories of vehicle, is very effective in driving manufacturers to improve the standards of performance within each category. But if consumers choose larger or heavier vehicles, the overall level of fuel economy can decline. In these circumstances, differential vehicle tax systems can help encourage consumers to move in the same direction as producers, *i.e.* towards lower fuel consuming vehicles.

It seems likely, depending on circumstances, that the best outcomes will be achieved where regulatory standards are supported by financial incentives, for example by aligning tax and regulatory systems by class of vehicle.

Fiscal systems also provide the opportunity to recognise that some technologies for improving fuel efficiency have a negative impact on local pollutant emissions, for example by encouraging a switch to diesel vehicles. To help avoid these negative impacts, tax schemes can be designed to pursue both improvements in fuel efficiency and the reduction of local pollutants. Such systems exist in Germany, Sweden and Japan.

Box 4.4 ► Vehicle scrappage schemes in Europe: life-cycle impacts on CO₂ emissions

Early scrappage or retirement of vehicles can speed stock turnover and the benefits that come with this turnover, such as lower pollution, better fuel economy and more manufacturing jobs. However, there are a number of pitfalls with scrappage schemes and various studies have shown that most are unlikely to provide large benefits or be very cost-effective (ECMT, 1999 and 2009 update, under development at the International Transport Forum). The pitfalls include:

- The tendency to retire vehicles that are not driven very much (so do not actually pollute or consume very much).
- The transitory nature of benefits (vehicles would be retired eventually anyway, so there are no permanent changes brought about by scrappage schemes).
- The relatively high “bounty” price that must be offered per vehicle to encourage owners to scrap their vehicles, compared to the value of the transitory benefits.

On the other hand, a well-designed programme could succeed in replacing some gross emitters with very clean vehicles, and guzzlers with fuel “sippers”.

In the European Union, in the first semester of 2009, 12 countries have implemented vehicle scrappage schemes, in part to stimulate purchase of new cars (ACEA, 2009c). Table 4.5 outlines the various schemes. Incentives per scrapped vehicle range from EUR 675 to 2 500. Some of the schemes include a requirement that the replacement vehicle must be low CO₂ emitting (i.e. very fuel efficient). Other schemes require a maximum pollution threshold.

Table 4.5 ► Scrappage schemes in Europe, 2009

Country	Incentive	Vehicle age	Conditions	Duration
Austria	EUR 1 500	> 13 years	- Local Pollutant Level* - Dealers pay 50% of the incentive - Total envelope EUR 45 m	01.04.2009- 31.12.2009
France	EUR 1 000	> 10 years	- CO ₂ emission Level - Estimated cost EUR 600 m/y	04.12.2008- 31.12.2009
Germany	EUR 2 500	> 9 years	- Local Pollutant Level - Used car purchased maximum 1 year old - Total envelope EUR 5 bn	14.01.2009- 31.12.2009
Italy	EUR 1 500- 5 000 (cars)	> 9 years	- Local Pollutant Level - CO ₂ emission Level	07.02.2009- 31.12.2009
	EUR 2 500- 6 500 (LCVs)		- Fuel Type dependant	(registration until 31.03.2010)

Table 4.5 ► **Scrappage schemes in Europe, 2009** (continued)

Country	Incentive	Vehicle age	Conditions	Duration
Portugal	EUR 1 000	> 10 years	- CO ₂ emission Level	01.01.2009- 31.12.2009
	EUR 1 250	> 15 years		
Romania	EUR 900 approx.	> 10 years	- Maximum 60,000 cars	01.02.2009- 31.12.2009
Spain	Interest-free loan up to EUR 10 000 (Plan VIVE)	> 10 years or > 250 000 km	- New car value maximum EUR 30 000 - CO ₂ emission Level	01.12.2008- 01.10.2010
	EUR 2 000	> 10 years (purchase new)	- Manufacturers pay 50% of the incentive	18.05.2009
	(Plan 2000E)	> 12 years (purchase used)	- CO ₂ emission Level	
			- Maximum 200,000 vehicles	
Luxembourg	EUR 1 500- 1 750	> 10 years	- CO ₂ emission Level	22.01.2009- 01.10.2010
Cyprus	EUR 675- 1 700	> 15 years	- EUR 675 for simple scrapping - Depending on Fuel consumption	Ongoing
Slovakia	EUR 1 000- 1 500	> 10 years	- New car value maximum EUR 25 000 - depend on dealers' contribution	09.03.2009- 25.03.2009
The Netherlands	EUR 750- 1 000	> 13 years	- Petrol cars/light commercial vehicles - Age of the vehicle	2009-2010
	EUR 1 000- 1 750	> 9 years	- Diesel cars/light commercial vehicles - Age of the vehicle - New car/van equipped with particulate filter	
ThenUntied Kingdom	GBP 2 000	> 10 years	- Manufacturers pay 50% of the incentive - GBP 300 million envelope	18.05.2009- 03.2010

*: The emission level can apply to the scrapped vehicle or to the new replacement vehicle, depending on the scheme.

Source: Adapted from ACEA, 2009c.

Table 4.6 ► GHG from vehicle production and use for Baseline and BLUE Map scenarios

	CO ₂ emitted during vehicle lifetime (in tCO ₂)	2005	2030	2050
Baseline	GHG From Production	5	5	4
	GHG from Use	50	33	32
	Share from production	10%	15%	14%
BLUE Map	GHG From Production	5	3	2
	GHG from Use	50	14	2
	Share from production	10%	22%	100%

Note: GHG from production of vehicles in BLUE map represents a rough estimate. GHG from production for Baseline, vehicle lifetime, average fuel economy and annual travel from IEA Mobility Model.

Table 4.7 ► Optimum retirement age for lowering GHG emissions taking production and use into account

Retirement age to minimise GHG emissions (years)	Share of vehicle's production GHG emissions over vehicle use GHG emissions (%)			
	10%	15%	25%	35%
0.25%	23	29	37	44
0.50%	17	20	26	31
0.75%	13	17	21	25
1.00%	12	14	18	22
1.25%	10	13	17	20
1.50%	10	12	15	18
2.00%	8	10	13	15
2.50%	7	9	12	14
5.00%	5	6	8	10

Source: adapted from Van Wee (2000)

■ 2000-2005 evolution

■ 2010-2050 Baseline evolution

■ 2010-2030 BLUE Map evolution

It is important to highlight that vehicle manufacturing (including materials extraction, processing, manufacturing, assembly and recycling) also consumes a significant amount of energy that can release GHG into the atmosphere. When adopting scrappage schemes to accelerate the renewal rate of vehicles in the fleet, the GHG share from vehicle production and disposal becomes larger as vehicle life shortens. It also becomes larger as the emissions from vehicle use drops, as it does over time – dramatically so in the BLUE scenario.¹ Table 4.6 shows the

1. Vehicle production GHG emissions for the BLUE scenario are indicative as no detailed estimates have been made for changes in manufacturing processes. But manufacturing emissions in the ETP 2008 BLUE scenario drop dramatically by 2050.

GHG share from vehicle production relative to vehicle use during the expected vehicle life time by year and scenario.

In both cases, the share is increasing, meaning that the production process is gaining importance in the vehicle life-cycle evaluation. Van Wee (2000) showed that there is an optimum when considering the rate of renewal and the decrease of fuel consumption. Table 4.7 shows the optimum fleet renewal rate for several fuel consumption annual improvement rates, and for several share of production GHG emissions over use emissions.

On-road fuel efficiency

4

Improving the tested technical efficiency of vehicles is only one means of reducing fuel use and CO₂ emissions from motor vehicles. Improving performance in actual on-road conditions is also important. Fuel economy on the road can be improved by such aspects as:

- Improvements in the efficiency of vehicle components, such as air conditioning and lighting, that are not specifically or fully tested in formal fuel economy rating systems.
- Improvements in the fuel efficiency of after-market equipment.
- Better driving styles.
- Improved vehicle maintenance.
- Reductions in traffic congestion.

The discussion in this chapter focuses on the first three of these areas. Improving vehicle maintenance becomes less of a concern as vehicles are increasingly built to require little maintenance on the part of drivers. Reducing traffic congestion is an important area for improving fuel economy, although it should be considered as part of a broader effort to restrain the growth in vehicle travel and encourage modal shifts. This is also discussed in Chapter 5.

Vehicle components not covered in fuel economy tests

Most of the vehicle fuel economy testing systems around the world test a similar range of efficiency aspects. These include engine and drivetrain losses, vehicle idling, aerodynamic drag and inertia, with different weightings being given to different aspects in different systems.

These systems do not generally cover aspects such as air-conditioning systems, lighting and the replacement parts for vehicles that may have different efficiency characteristics than the original equipment, such as tyres and lubricating oils. There is therefore little incentive for manufacturers to improve these aspects.

Some steps to include accessories have begun to be taken. For example, the US EPA recently issued a new system for calculating fuel economy in which more and less efficient air-conditioning systems on different vehicles are evaluated.

Tyres

Recognising that, as discussed in chapter 3, the fitting of the best replacement tyres and the more effective maintenance of tyre pressures could save about 3% of the fuel used in LDVs (equivalent to around 70 Mtoe and 190 MtCO₂ in the medium term world wide), a number of initiatives are underway or planned to improve the efficiency of tyres in use. They include:

- **European Union:** On 23 May 2008, the European Commission issued a proposal for a regulation on tyres (European Commission, 2008b). If approved, this will require that low RR tyres and tyre pressure monitoring systems are obligatory from 2012. Additionally, explicit safety requirements also play a large role in the legislation.
- **United States:** The Energy Independence and Security Act of 2007 (EISA, 2007) directs NHTSA to create a national consumer education programme on tyre energy efficiency. In the State of California, 2003 legislation requires tyre manufacturers of light-duty tyres sold in the state to report fuel economy information. It also mandates a rating system and minimum efficiency standards. California is currently working on promulgating regulations establishing requirements under this law.
- **Japan:** In December 2008, the Japanese government established a committee comprising representatives from the tyre and vehicle industries, academia and related ministries to discuss appropriate measures to promote fuel efficient tyres. In March 2009, it published a report recommending early action to introduce various measures regarding tyre RR test procedures, a labelling scheme and tyre pressure monitoring systems.
- **International Standards Organisation (ISO):** The absence of a globally harmonised test procedure to measure RR has been one of the impediments to better co-ordinated international efforts to improve tyre fuel efficiency. A reference tyre RR measurement method is expected to be adopted as an ISO Standard in 2009. Given that tyres are globally traded, this international standard can be expected to benefit both consumers and industry. The ISO standard, although not yet finalised, forms part of the proposed EU regulation on tyres.
- **UNECE/WP29:** The World Forum for Harmonisation of Vehicle Regulations continues to discuss mandatory fitting of tyre pressure monitoring systems. These discussions began in 2007 but do not have an anticipated completion date.

Against this background, the IEA recommends that governments should adopt the new ISO standard test procedures for measuring the RR of LDV tyres with a view to establishing appropriate labelling systems, and possibly maximum RR limits where appropriate. Governments should also adopt measures to promote the proper inflation of tyres. This should include making mandatory the fitting of tyre pressure monitoring systems on new road vehicles.

Other components

Similar consideration is warranted for cooling technologies and lighting. But recognising that these components are generally only chosen by vehicle manufacturers, rather than by customers, different approaches may be needed to raise customer awareness. For example, governments may consider policy options such as reviewing fuel efficiency test procedures to better reflect the energy use of components, setting minimum efficiency performance standards for, and adding specific information on, components to existing consumer information schemes. Technological options may also exist to improve the fuel efficiency of a range of component systems, such as improved controls for cooling systems.

Eco-driving and intelligent transportation systems

Eco-driving

Improving driving techniques, or eco-driving, can have a significant impact on on-road fuel efficiency and CO₂ emissions. It can also contribute to improving safety, reducing noise and stress. In some countries, eco-driving programmes are an important part of road safety programmes.

Eco-driving is the operation of a vehicle in a manner that minimises fuel consumption and emissions. It would include:

- Optimising gear changing.
- Avoiding vehicle idling, e.g. by turning off the engine when the vehicle is stationary.
- Avoiding rapid acceleration and deceleration.
- Driving at efficient speeds. The most efficient speed for most cars is between 60 km/h and 90 km/h. Above 120 km/h, fuel efficiency reduces significantly in most vehicles.
- Reducing weight by removing unnecessary items from the car, and reducing wind resistance by removing attachments such as ski racks.

Taken together, these steps could save up to 20% of the fuel used by some drivers and possibly as much as 10% on average across all drivers on a lasting basis.

In November 2007, the IEA, in co-operation with the International Transport Forum, held a workshop to review current experience around the world in implementing and promoting eco-driving. The initiatives reviewed in the workshop are shown in Table 4.8.

Presentations at the IEA workshop quantified the impacts of individual schemes on both a short-term (less than three years) and medium-term (more than three years) basis. Immediately after eco-driving training, average fuel economy improvements of between 5% and 15% were recorded for cars, buses and trucks. Over the medium term, fuel savings of around 5% were sustained where there was no support beyond the initial training or around 10% where further feedback was available.

Table 4.8 ► **Eco-driving programmes and target improvements in different countries or projects**

Country	Method	Short-term	Mid-term
Netherlands	National programme	10% to 20%	5% to 10%
Austria	National programme	10% to 15%	5% to 10%
Japan	Smart driving contest	25%	
Japan	Idle stop driving	10% ^w	
Japan	Ecodrive workshop	12%	
Japan	Average mileage workshop	26%	
Sweden	Driver training courses	5% to 15%	
Austria	ÖBB Post Bus Best Practice training courses, competition, monitoring, feedback	10%	
Austria	Ecodriving competitions for licensed drivers	30% to 50%	
Austria	Mobility management for company fleets	10% to 15%	
UK	Freight Best Practice	10%	
UK – Lane Group			4%
UK – Walkers			9%
Deutsche Bahn	Training courses, monitoring, feedback, rewards		3% to 5%
FIA – AASA (South Africa)	Driver training courses	15%	
FIA – Plan Azul (Spain)	Training and test	14%	
FIA – ADAC (Germany)		25%	
FIA – ÖAMTC (Austria)	Training	6%	
FIA – JAF (Japan)	Training and skills practice	12% to 16%	
Shell	Pilot training programme	5% to 20%	
Ford	Training courses and trip/driving style analysis	25%	10%
Nissan		18%	

Note: See IEA Workshop (2007b) for further details on individual projects.

A study of an eco-driving initiative in the Netherlands suggests that eco-driving projects can achieve CO₂ savings at an average cost of less than EUR 10/t CO₂ saved. This figure, however, includes only government spending. It takes no account of the co-funding by partner organisations and private companies on commercial basis.

Given the potential for very large fuel savings, some eco-driving initiatives are being undertaken without the help of government measures. Fleet operators are incentivised by cost savings to take action themselves, and eco-driving initiatives can

be shown to support wider claims to responsible or sustainable entrepreneurship. Even so, the up-front costs of encouraging and tracking eco-driving tend to be more visible than the long-run savings. There is potential for many more fleet operators and drivers to introduce eco-driving.

Experience of existing initiatives suggests that they are most successful when they incorporate:

- **Dealing with information failure:** communication campaigns that directly or indirectly draw attention to practical driving tips have been successful in many countries. Beyond providing information about the way to drive to reduce fuel consumption, GHG emissions and accident rates, communication is most effective when eco-driving is promoted with advertising inspired by commercial marketing. The presentation of the message has to be both teasing and appealing. It has to avoid casting doubt on the driving skills of the target groups. Presentations at the IEA workshop suggested that communication campaigns, supported by information materials, can achieve around 5% savings for individuals who respond to a campaign.
- **Driver training:** eco-driving is already required to be taught to learner drivers under EU regulations. Presentations at the IEA workshop showed that implementing eco-driving within the driver licence education and examination process can bring significant savings. Participants emphasised the role of partnership with driving instructors. Including eco-driving as a part of test criteria for awarding both commercial and general driver licences is recommended as a very effective measure to convey the eco-driving message to future licensed drivers.
- **In-car equipment:** a number of equipment strategies are available to encourage eco-driving. In-car equipment (such as gear shift indicators, cruise controls and on-board fuel economy computers that show, for example, real-time and average fuel economy), can all help improve fuel economy. Instrumentation alone can achieve an estimated 5% savings. In-car gauges can further improve driver performance after training as they create an incentive to try to improve performance. The Netherlands has promoted on-board instrumentation in new cars through fiscal incentives for a number of years, and has achieved very high levels of uptake. More than 75% of new cars now incorporate such equipment.
- **Building partnership programmes:** enlisting the help of other organisations, such as automobile clubs, industry associations and consumer organisations, can also improve the effectiveness of government expenditure.

Finally, eco-driving can only succeed if consistent messages are given to drivers. Consumers should not be encouraged to undertake eco-driving courses while being offered on a regular basis new vehicle versions capable to accelerate more quickly than the previous generation of similar vehicles (and, thus, implicitly inviting non-eco-driving). If this is the case, the success of eco-driving schemes is likely to remain limited, especially in the longer term.

Intelligent transportation systems

Intelligent transportation systems (ITS) include a wide range of electronic and telematic technologies to improve communication within and control of transportation systems. Overall, these are envisioned to make transportation safer and more efficient, for example by reducing congestion and helping travellers optimise journey planning. These should also help make transport more energy efficient.

The costs of accidents and congestion are significant worldwide. The World Health Organization (WHO) estimates total worldwide traffic fatalities in 2009 will top 1.2 million. Traffic accident fatalities in the United States and Europe both average 40 000 per year. The costs of traffic accidents in the United States and Europe are estimated close to USD 150 billion and EUR 200 billion per year, respectively. Congestion similarly imposes large costs on individuals and society. For example, in the United States the cost of congestion for 2008 was estimated at USD 87 billion, not to mention the hours of driver time and fuel losses (Table 4.9). If ITS is able to reduce these costs by even a few percent, the savings in terms of lives and money will be significant.

Table 4.9 ► **Estimated annual cost of congestion in the United States**

	Impact of congestion
Driver hours	4.2 billion hours, or 36 hours per driver
Cost of congestion	USD 87 billion USD 750 per traveller
Fuel loss	2.8 billion gallons

Source: TTI, 2009.

In the future, road vehicles may be able to communicate with the vehicles around them to avoid collisions and harmonise individual vehicle speeds and lane changes so that traffic flows freely with less need for acceleration and deceleration. Onboard radar and computers will facilitate these goals. First-generation applications of these technologies are increasingly present on vehicles, for example rear-obstruction sensors for parking and real-time fuel economy readouts. The interfaces between technology and driver will improve, providing much better information to help drive safely and efficiently. Eco-driving will benefit from ITS by integrating driver goals and real-time engine performance data to optimise engine performance and fuel economy. Allowing the vehicle ITS system to coach the driver on efficient driving will help make eco-driving a habit. As discussed above, eco-driving can improve fuel efficiency by 10% for drivers that use it; ITS systems can help maximise this benefit.

Improving the flow of traffic both on city streets and on highways significantly improves fuel economy. This is especially true for heavier vehicles. Therefore, ITS systems that can adjust the timing of traffic lights based on current traffic loads can save energy and reduce emissions by creating a steadier speed profile and less idling. As discussed in Chapter 5, congestion pricing systems (e.g. adjustable rate toll lanes) are another tool for improving the flow of traffic. The monetary incentive

structure encourages more efficient trip planning and shifting traffic to lower demand time periods or routes.

Integrating real-time monitoring infrastructure into the road network can provide valuable information to traffic management systems. Eventually, the use of wireless internet technology and GPS systems may further help to automate directing traffic to avoid congestion. Such systems are being implemented in some countries, but should be aggressively pursued in nearly all countries, as some technologies are widely available and costs are affordable, and can be quite low per unit fuel saved. Traffic light synchronisation and provision of GPS-based traffic information may be among the best near-term options.

However, it is important that measures to improve traffic flow or otherwise make driving easier and faster do not trigger “induced demand”, i.e. more driving. As described in Chapter 5, it is important to manage the demand for car driving as well as the supply of available road space. Congestion-based road pricing is an excellent management tool as part of a broad ITS implementation strategy.

ITS systems can also help to improve transit systems significantly, both via better routing and dispatching (e.g. of buses, using GPS information on where they are located) and by providing better real-time information to travellers on expected waiting times. Delivery of such real-time information via the internet, cell phones, and at actual bus and rail stops has proven immensely popular with travellers in many cities around the world. It appears to be a priority investment area for all transit systems.

Beyond optimising the routing and control of vehicles on the road, the condition of the road surface is another area for ITS applications. Systems that monitor weather and road conditions, and transmit that information to on-board vehicle ITS tools have the potential to reduce accidents and the congestion resulting from those accidents. In the future, it may even be possible to adjust road surfaces to compensate for weather.

All transport modes can benefit from ITS. For example, GPS monitoring of aircraft could allow for continuous descent landing patterns to reduce fuel use and reduce the risks of collisions. Electronic freight management can reduce delays in shipping by eliminating paperwork processing and assisting with the timing and location of transferring freight between modes.

Chapter 5 PASSENGER TRAVEL

Key findings

- ▶ *Travel statistics for most countries are subject to numerous uncertainties. But it is estimated that, in 2005, total global passenger travel using motorised modes was about 40 trillion kilometres, or about 6 000 km per person. The Baseline scenario for passenger travel projects this total to double between 2005 and 2050, to around 80 trillion km a year or 9 000 km per person. In the High Baseline scenario, travel increases even further to nearly 12 000 km per person per year. Due to population and income growth, most of the Baseline travel growth is accounted for by a tripling of travel in non-OECD countries. Total travel in OECD countries is projected to increase by around 35%. But travel per capita in 2050 is expected to remain far higher in OECD countries, increasing from 16 000 km per person per year in 2005 to about 20 000 km in 2050. In non-OECD countries, it doubles from 4 000 km to about 8 000 km per person per year. The difference is mainly due to long-distance (especially aviation) travel, while urban travel levels per capita in OECD and non-OECD become much closer.*
- ▶ *Baseline travel growth in both OECD and non-OECD countries is dominated by LDVs, two-wheelers and air travel. Mass transit also grows, but its modal share declines as LDV travel grows much more quickly. In non-OECD countries, the share of all motorised travel (on a total passenger-kilometre basis) undertaken by bus and rail drops from 50% in 2005 to about 30% by 2050. In OECD countries, it retains a consistently low share of about 10%¹ from 2005 to 2050.*
- ▶ *Although only rough estimates can be made to distinguish urban from non-urban travel for many countries, the IEA's initial estimates indicate that for urban travel in OECD countries in 2005, bus and rail travel comprised about 30%. In non-OECD countries, bus and rail account for about 80% of urban motorised travel. In 2050 in the Baseline scenario, this is almost unchanged in OECD countries but drops to 55% in non-OECD countries. Two-wheeler urban travel in non-OECD countries increases from about 10% in 2005 to 15% in 2050, and increases even more in some regions such as Asia.*
- ▶ *In the Baseline scenario, some of the least efficient modes of travel, such as LDVs and aircraft, come to dominate travel by 2050, while some of the most efficient modes, such as bus and rail, experience a strong decline in modal share. In OECD countries, 25% of non-urban travel, including inter-urban, small town and rural, was undertaken by air in 2005. LDV travel accounted for 65% of all travel with the remaining 10% by other modes, including rail and bus. In the Baseline scenario for 2050, these proportions become almost 50% for air, 40% for LDVs and 10% for other modes. In non-OECD countries in 2005, about 20% of motorised travel was*

1. Throughout this chapter, unless otherwise specified, travel is reported in km, not numbers of trips. Thus, modal share estimates are reported on a total km basis, not on a trip share basis, as is often the case.

by air, 20% by LDV, and 60% by bus, rail and other modes. For 2050, this becomes 35% by air, 35% by LDV and 30% by other modes in the Baseline scenario.

- ▶ This chapter presents a new IEA scenario, *BLUE Shifts*, which examines the possibility of changing future patterns of travel toward more efficient modes or, in some regions, preserving the current shares of these modes. In this scenario, the Baseline increase in LDV travel is shifted to rail, bus and non-motorised modes. Of the Baseline increase in air travel, most is shifted to high-speed rail and coach. A significant share of the Baseline increase in both LDV and air travel, especially in OECD countries, is assumed to be avoided, being displaced by increased use of teleworking and greater use of videoconferencing in lieu of air travel. The *BLUE Shifts* scenario also assumes that in some non-OECD regions, particularly Africa, a rapid expansion of rail and bus services triggers increased travel in addition to that derived from modal shifts.
- ▶ It will not be easy to achieve any significant level of modal shift away from the Baseline trend. But the analysis in this chapter suggests that with strong and effective policies, worldwide LDV travel in 2050 might be cut by 25% compared to the Baseline scenario, resulting in a 50% (instead of 80%) increase over 2005 levels. Air travel is also cut by 25% in 2050 compared to the Baseline, resulting in a tripling rather than a four-fold increase over 2005 levels. It should also be noted that these represent nearly 50% reductions in 2050 when compared to travel growth in the High Baseline. Though greater shifting may certainly be possible, these represent challenging targets; in any case, the primary objective is to estimate what impact a given level of shifting might have on energy use and CO₂ reductions.
- ▶ The overall impact of the *BLUE Shifts* scenario is to achieve about a 20% reduction in energy use and CO₂ emissions in 2050 compared to the Baseline scenario. If policies were implemented rapidly, nearly this much could be achieved by 2030. When combined with other changes to vehicles and fuels (e.g. in the *BLUE Map/Shifts* scenario), as described in Chapter 1, the overall CO₂ reduction reaches 70% compared to the Baseline in 2050.
- ▶ By 2050, if vehicles and fuels are not as dramatically decarbonised as they are in the *BLUE Map* scenario, the effect of modal shifting increases. Encouraging travel on the most efficient modes and reducing travel where sensible will not only provide a range of important co-benefits such as pollutant emissions reductions, but also provide a GHG reduction strategy that will become increasingly important if technology solutions do not provide the deep GHG reductions across all modes envisioned in the *BLUE Map* scenario.
- ▶ The second half of this chapter covers a range of policy measures that could help to achieve the outcomes implicit in the *BLUE Shifts* scenario. These include: better land-use planning; telematics; electronic road pricing, including intelligent transport systems; car sharing systems; stronger parking measures; investments in better bus systems; and investments in infrastructure to promote cycling and walking. Other measures will be needed as well, such as better information systems for travellers. The discussion here explores the potential travel impacts and costs for a selection of

potentially important measures, to help design a modal shift strategy in OECD and non-OECD regions.

- ▶ *The available evidence for many of these measures, though often limited, suggests that when all the costs and benefits are taken into account, the net benefits in terms of fuel savings, reduced traffic congestion, travel time savings, reduced pollutant emissions, and improved safety can be significantly larger than the costs. In such cases, these measures make sense even before accounting for the CO₂ benefits. The resulting GHG reductions can be seen as a highly desirable co-benefit of measures that are fully justified on other grounds. As a result, the associated GHG reductions come at negative socioeconomic cost. Even when only direct costs are taken into account, GHG reduction costs for the measures considered typically amount to between USD 50 and USD 150 per tonne of CO₂ eq saved, lower than for some other transport options. Much more cost-benefit work is needed for most measures, in more cities and countries, to strengthen estimates. This is especially necessary given that the cost-effectiveness of some modal shift measures may vary significantly on a case-by-case, country-by-country or city-by-city basis, and between best practice and less well-designed examples.*

Introduction

The carbon intensity of travel depends not only on technical issues such as the characteristics of vehicles and the fuels they use, but also on the choices made by people as to how much they travel and the means by which they do so.

This chapter looks at trends in passenger travel in different regions. It then examines how policy developments might influence those trends towards more sustainable and less energy-intensive travel, which in many cases would also achieve better mobility and a range of wider benefits.

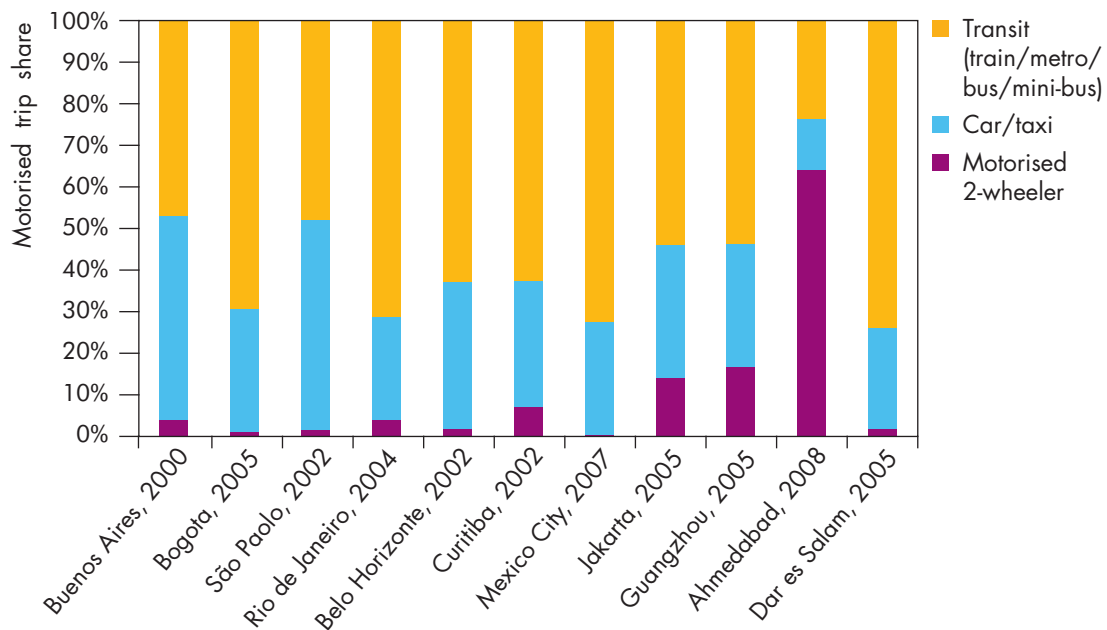
Travel levels and typical modes of travel vary widely between different countries and between individuals within the same country. The primary focus of this analysis is on trends in travel and in modal shares of travel. It does not attempt to address the reasons why people travel or the factors that influence demand in different countries or for different types of travel.

Current transport systems are imperfect in many ways, raising issues of congestion, safety and energy insecurity, and damaging the environment. In OECD countries, the policy challenge is to identify ways in which travel might be conducted differently, to maintain or improve mobility and access while reducing negative impacts and improving sustainability. At the same time, policies need to be devised in places that currently have low but rising levels of travel per capita such as in much of the developing world, and achieve greater mobility and improved accessibility in an efficient, sustainable manner. In many places, this means preserving the share of travel by the most efficient modes through strong investments in these modes and

Table 5.1 ▶ Trip modal shares of private motor vehicles in selected cities

City	Private motor vehicle mode share of trips
Hong Kong	20%
Amsterdam	30%
Berlin	45%
London	50%
Rome	58%
Sydney	75%
Calgary	90%
Houston	95%

Source: UITP Millennium Cities Database, 2001.

Figure 5.1 ▶ Shares of trips in selected cities and years, motorised modes

Source: Various, compiled by ITDP, 2008.

Key point

In cities located in developing countries, mass transportation represents the majority of motorised trip shares.

policies encouraging their use, while discouraging strong travel growth by the least efficient modes.

As shown in Energy Technology Perspectives 2008, ETP 2008 (IEA 2008) and elsewhere, cities in which people travel predominantly in personal motorised vehicles (such as cars and SUVs) use much more energy per capita than cities

in which people use public transport and non-motorised modes of travel (NMT) such as bicycling and walking. People's preferences for personal motorised travel, even at similar income levels, vary widely from city to city. Table 5.1 shows, for a selection of cities with incomes between USD 20 000 and USD 30 000 per capita, the percentage of all trips taken in private vehicles. There are many reasons for these differences and it would not be easy for any city to change rapidly its share of private vehicle use. But Figure 5.1 shows that there are many different ways in which cities can operate. It also suggests that there is scope, particularly for cities that are still growing rapidly around the developing world, to make choices about the way in which they want patterns of transport to develop.

Figure 5.1 shows the share of trips that are undertaken using motorised vehicles in a number of cities in the developing world for which recent data is available.² Most of these cities rely on public transit for most of their travel. The main exception is Ahmedabad, India, where motorised two-wheelers are the dominant mode of transport.

IEA travel projection framework

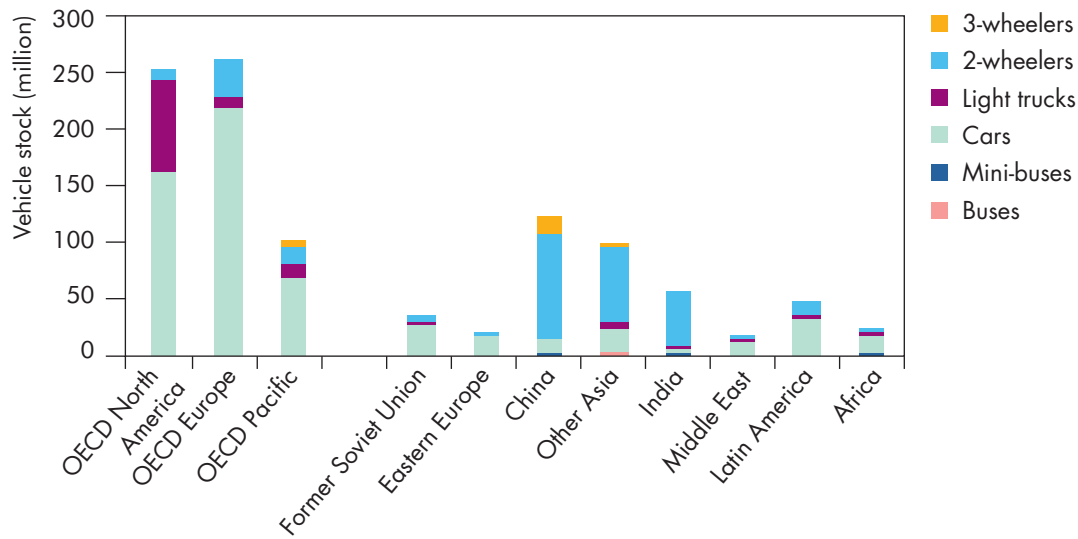
Trip-based data is available only on a very limited basis, rarely at a national level and for cities often on an intermittent and irregular basis. To develop a baseline for modal travel shares at national and regional levels, the analysis in this chapter is based on a different approach, starting from vehicle data in the IEA Mobility Model (MoMo). Using MoMo data on the stocks of different types of vehicles, together with estimates of the average annual travel per type of vehicle and an average load factor (the average number of people per trip), an estimate can be made of the total passenger travel by mode in each country/region.

MoMo is developed at a regional and, in some cases, national level, rather than at city level. For the current analysis, an initial attempt has been made, as described below, to separate out urban and non-urban travel in order to give at least a rudimentary picture of the ways in which these may vary in different parts of the world. This analysis should be seen as preliminary; much more data is needed to better calibrate this work.

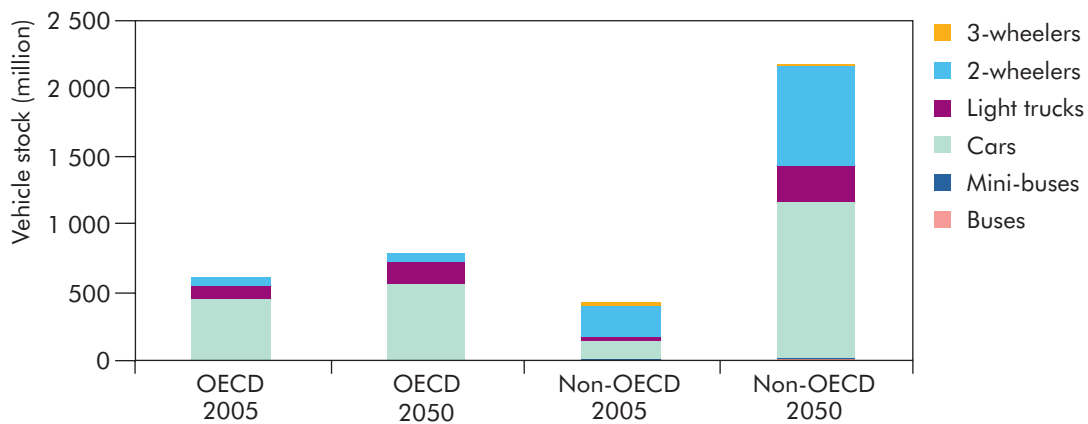
Non-motorised modes are not included in the current analysis. The IEA has found few reliable estimates of average NMT per year at a national or any other level. But NMT is highly significant, especially in poorer parts of the world. In some countries, half or more of all trips may be made on foot, although this, not surprisingly, translates into a much smaller share of all kilometres of travel. Where relevant, the importance of NMT is highlighted in the following discussion.

The first step in the analysis was to generate national and international passenger travel estimates based on data on vehicle stocks, vehicle travel and load factors. IEA vehicle stock estimates are shown by region in Figure 5.2. Totals for OECD

2. The methodologies for collecting this data may vary considerably between cities so some caution is in order when comparing them. In particular, a few cities provided NMT data. NMT data have been excluded and motorised trips have been re-calibrated to 100%.

Figure 5.2 ► Total stock of motorised road vehicles, by region, 2005**Key point**

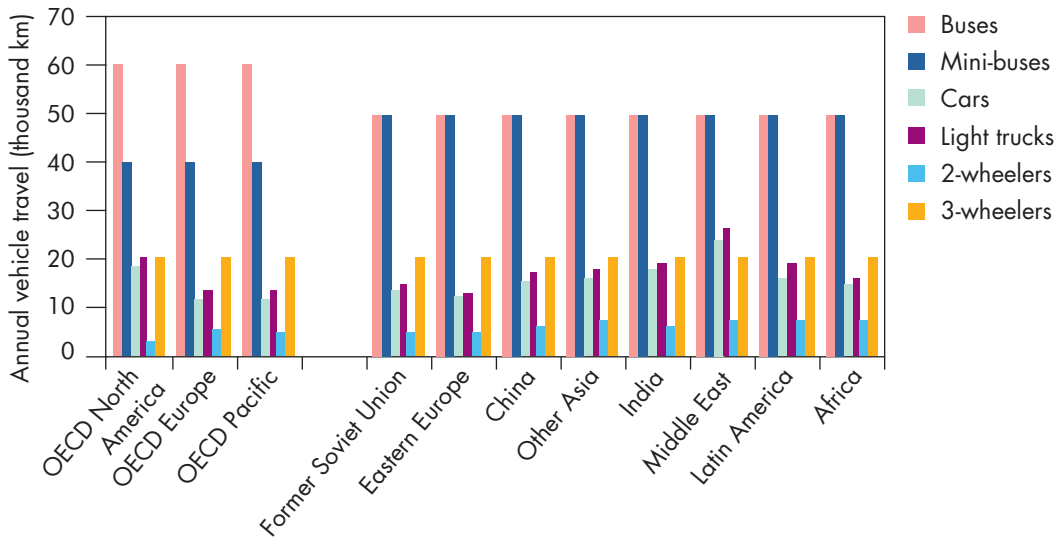
OECD countries possess 60% of the motorised vehicle stock, dominated by passenger LDVs.

Figure 5.3 ► Total stock of vehicles in OECD and non-OECD countries, 2005 and 2050**Key point**

The majority of vehicle growth will come from non-OECD countries in the decades to come.

countries and for non-OECD countries, along with the IEA Baseline projections to 2050, are shown in Figure 5.3.

Figure 5.4 shows the regional average travel per year by vehicle type in 2005. These are rough estimates based on partial data for a few cities and countries. These data need further verification through additional data collection. The average travel per vehicle per year is expected to remain close to current levels over the long run.

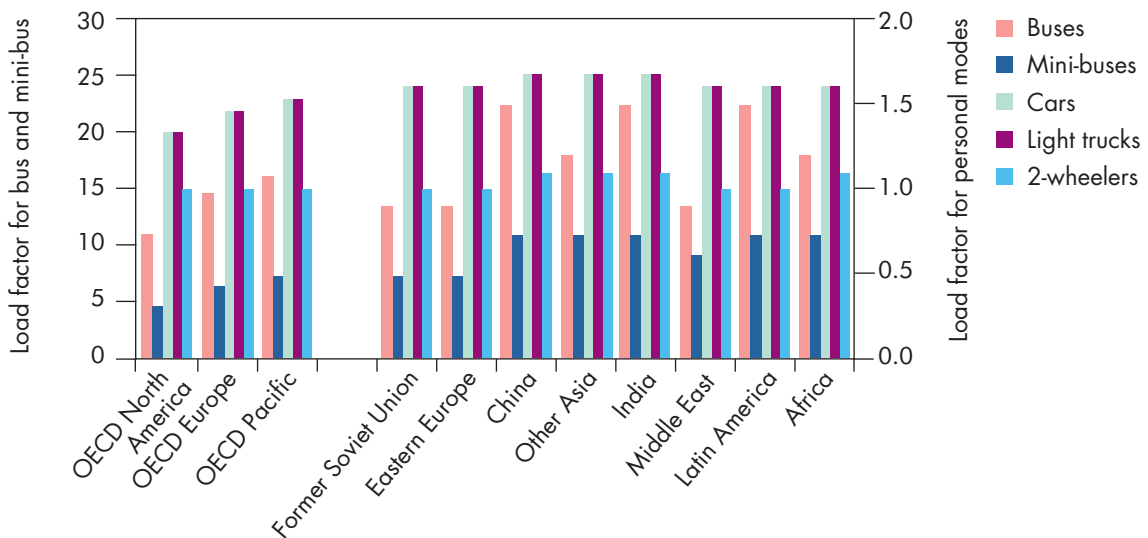
Figure 5.4 ▶ Average travel per year by vehicle type, region, 2005

Note: IEA estimates for buses and mini-buses.

Key point

Urbanisation rate, population density, energy prices and GDP per capita are key drivers to annual mileage from individual motorised modes.

The average load factor, in terms of numbers of people per vehicle, is also not widely or consistently available. It is estimated based on reports from surveys in a few countries and cities. MoMo estimates for 2005 are shown in Figure 5.5. Average load factors are lowest in North America. They are probably declining in

Figure 5.5 ▶ Average load factors by vehicle type, region, 2005 (passengers per vehicle)

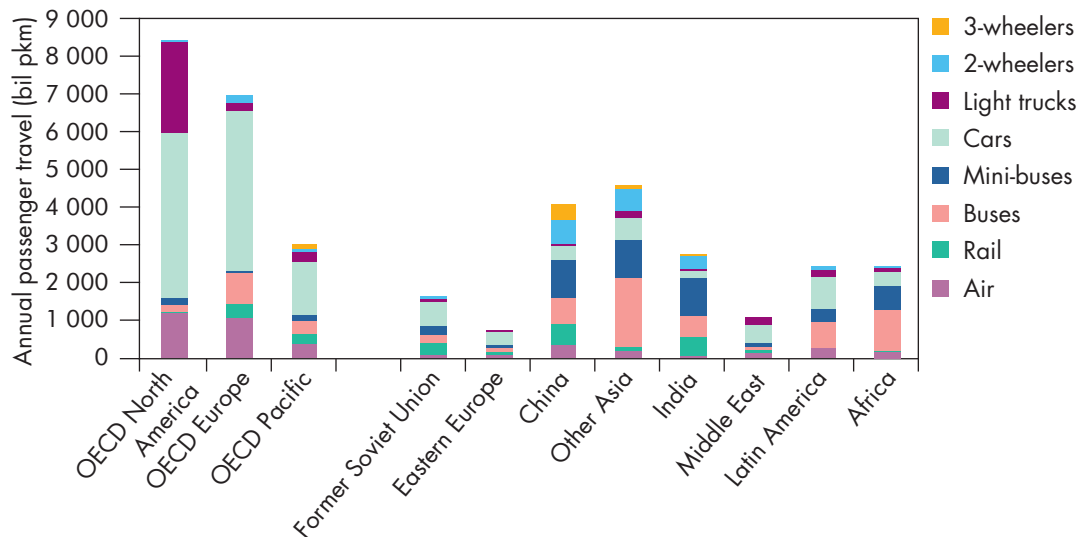
Key point

Non-OECD countries have higher load factors, mainly due to lower ownership rates.

most parts of the world, as more vehicles become available. The analysis assumes slowly declining load factors for most types of vehicles in the future.

Using these assumptions,³ the IEA analysis estimates the total motorised passenger travel by mode for each region as shown in Figure 5.6. This is shown in terms of kilometres of travel, unlike Figure 5.1 which is measured in terms of trips. Modes that are typically used for longer trips, such as air travel, have a much bigger share in kilometres than in trips. Figure 5.7 provides the same information on a per capita basis, showing much higher levels of travel per person in OECD than in non-OECD countries. India and Africa have the lowest levels of travel per capita.

Figure 5.6 ▶ Estimated total annual passenger kilometres by mode and region, 2005



Key point

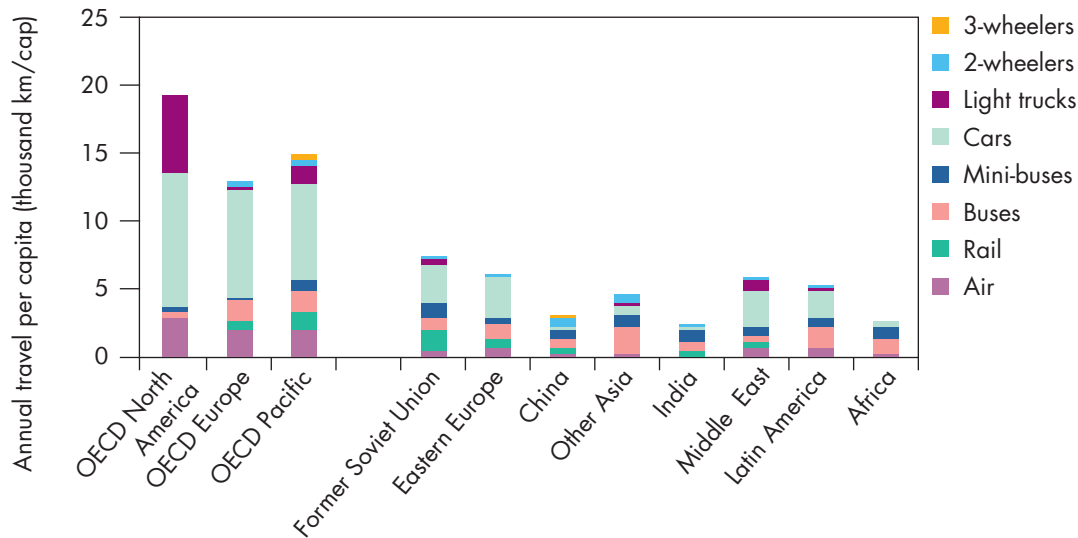
OECD countries are heavy users of least energy-efficient modes.

In Figure 5.8, total travel in OECD countries and non-OECD countries is shown for 2005 and in the Baseline projection for 2050. OECD travel grows relatively little. By contrast, non-OECD travel nearly triples, due both to strong population growth and to income growth. But as shown in Figure 5.9, OECD countries are projected still to have far higher average travel levels per capita than non-OECD countries in 2050, at around 19 000 km per person per year, compared to about 9 000 km per person per year in non-OECD countries.

Notwithstanding the uncertainties in much of the underlying data, the picture that emerges is that the distances travelled per person by motorised travel in OECD countries are much higher than in non-OECD countries, and are skewed toward

3. It should be emphasised that these derived estimates are based on data for vehicle stocks, travel per vehicle and load factor estimates, which may themselves be unreliable for many countries. Thus, the resulting estimates may contain significant errors, in particular for non-OECD regions where some vehicle stock and travel data is very uncertain. The estimates should be regarded as approximate only.

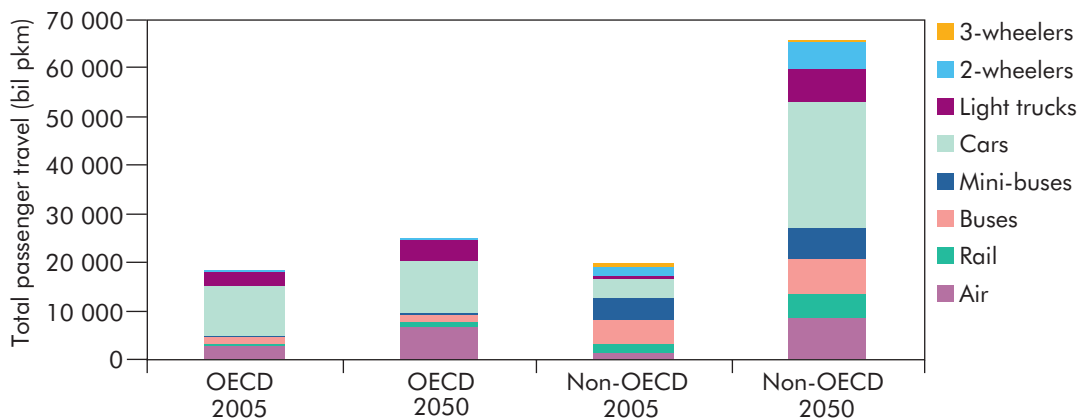
Figure 5.7 ▶ Estimated per capita annual passenger kilometres by mode and region, 2005



Key point

Non-OECD countries' inhabitants travel three- to five-fold less than OECD countries' inhabitants.

Figure 5.8 ▶ Passenger kilometres of travel by motorised mode: 2005 and Baseline scenario 2050, OECD and non-OECD



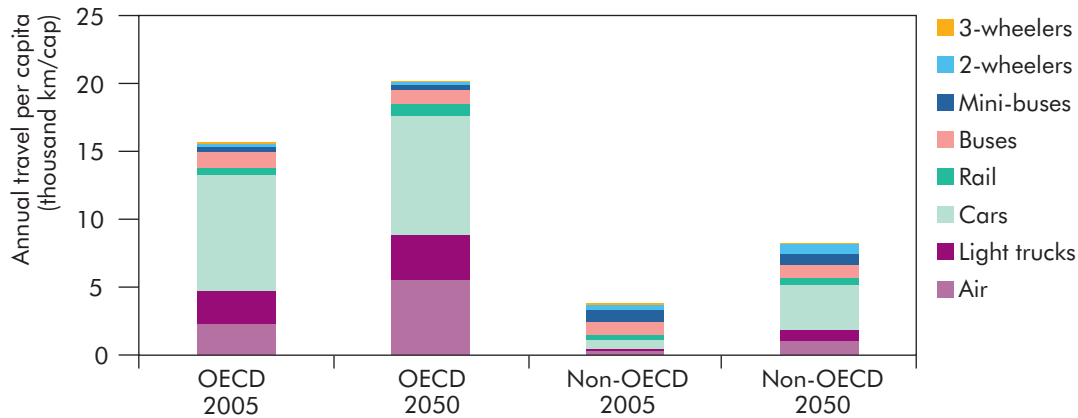
Key point

Non-OECD countries are projected to represent most of the mobility by 2050.

faster personal modes such as air, cars and personal light trucks. Total travel in non-OECD countries is currently similar to that in OECD countries, although by 2050 it is likely to be more than twice as high.

The IEA analysis has also attempted to distinguish between urban travel and non-urban travel. Given the quality of the available data, this is very approximate. Non-urban travel is taken to be all travel not occurring in major metropolitan areas:

Figure 5.9 ▶ Passenger kilometres of travel per capita: 2005 and Baseline scenario 2050, OECD and non-OECD



Key point

Non-OECD per capita mobility will still be one-third of OECD per capita mobility in 2050.

it includes inter-urban travel, virtually all air travel, and town and rural travel. On this basis, given the available information, rail travel is assumed to be 70% to 80% non-urban since inter-city rail systems carry passengers much further per trip than urban rail systems, and since there are few urban rail systems in most parts of the world. The full set of assumptions underlying the analysis is shown in Table 5.2. These percentages should be considered indicative. The IEA intends to improve and refine these as more data are collected in the future.

Table 5.2 ▶ Assumed passenger-kilometre shares of urban and non-urban travel in 2005, by mode and region

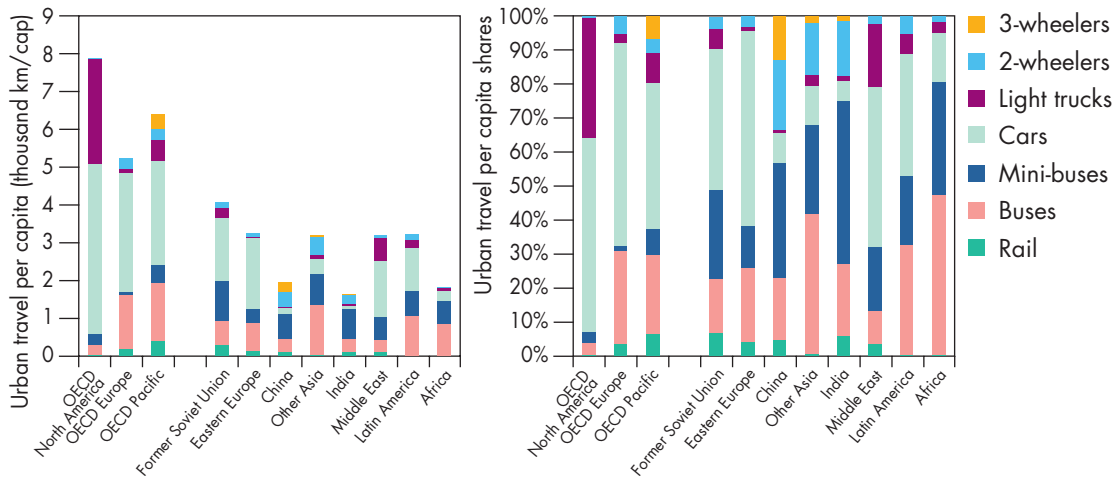
		Rail	Air	Buses	Mini buses	Cars	LTs	2-3 Ws
OECD North America	urban	20%	0%	80%	60%	50%	50%	50%
	non-urban	80%	100%	20%	40%	50%	50%	50%
OECD Europe / Pacific	urban	30%	0%	90%	60%	40%	40%	70%
	non-urban	70%	100%	10%	40%	60%	60%	30%
Rest of world	urban	20%	0%	70%	85%	60%	60%	80%
	non-urban	80%	100%	30%	15%	40%	40%	20%

Sources: IEA data and assumptions based on various sources.

The results of applying these assumptions, in terms of per capita urban passenger travel shares, are shown in Figure 5.10. This figure suggests that urban travel levels are less diverse between regions than non-urban travel levels. They still, however, vary widely, ranging from about 2 000 km per person per year in India, China, and Africa to 8 000 km per person per year in OECD North America. Urban passenger travel mode shares are also shown in Figure 5.10. In this respect, North America stands out as being quite different from other regions, with nearly 90%

of urban travel occurring in LDVs. LDV travel in no other region is estimated to be above 70%. In most non-OECD countries, bus and mini-bus travel accounts for a substantial share of urban motorised travel.

Figure 5.10 ▶ Estimated urban passenger travel per capita and mode shares, 2005

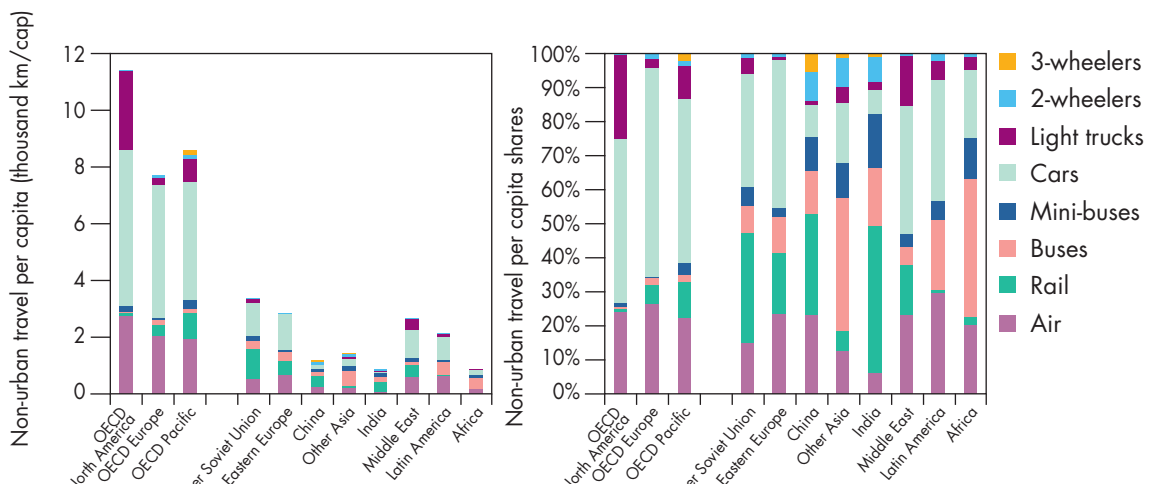


Key point

Urban mobility is car dominated in OECD countries and mass-transportation dominated in non-OECD countries.

Non-urban travel by region is shown in Figure 5.11. In most regions air travel ranges from 20-30% of passenger kilometres of travel. In OECD regions, non-urban travel by rail, bus and minibus together accounts for no more than 15% of all non-urban passenger kilometres, whereas in non-OECD regions it can account for up to 70%. Cars and light trucks account for almost all the remaining non-urban travel in OECD countries, and account for a substantial share in most non-OECD countries.

Figure 5.11 ▶ Estimated non-urban passenger travel per capita and mode shares, 2005



Key point

Non-urban mobility difference between OECD and non-OECD countries remains substantial, mainly due to average speed differences.

The BLUE Shifts scenario

This analysis provides a starting point for estimating how energy use and CO₂ emissions might change if people's travel patterns were to change in the future.

The overarching scenarios in relation to travel, vehicle and fuel characteristics, fuel use and CO₂ emissions are presented in Chapter 1. This chapter focuses on the travel aspects of potential future scenarios, based on three scenarios: the Baseline scenario, the High Baseline scenario and a new BLUE Shifts scenario. The BLUE Shifts scenario assumes that the demand for private mobility in LDVs in the Baseline and High Baseline scenarios is reduced by a combination of better urban planning, infrastructure improvements, better public transit systems (including bus rapid transit, light rail and inter-city high-speed rail systems) and policy measures that encourage use of these modes. This results in a shift away from trends found in the Baseline or High Baseline, but also it means less shifting away from more efficient modes in the BLUE Shifts scenario than what occurs in those scenarios.

In practice, the extent to which travel patterns will change over the next 40 years will be constrained by factors such as people's willingness to change their behaviour, the level of political will to require or stimulate such changes, limits on changes to the physical environment of cities, and constraints on levels of investment. Many assumptions could be made about the effects of different policy and planning approaches on future travel behaviour. But to illustrate one possible set of plausible outcomes, the central assumption adopted in the BLUE Shifts scenario is that growth in the more energy-intensive modes of travel, *i.e.* by LDV and air, is limited to a level 25% lower than the Baseline scenario level in 2050. This is equivalent to about a 50% average reduction in the growth of these modes in the High Baseline scenario, varying depending on mode and region.

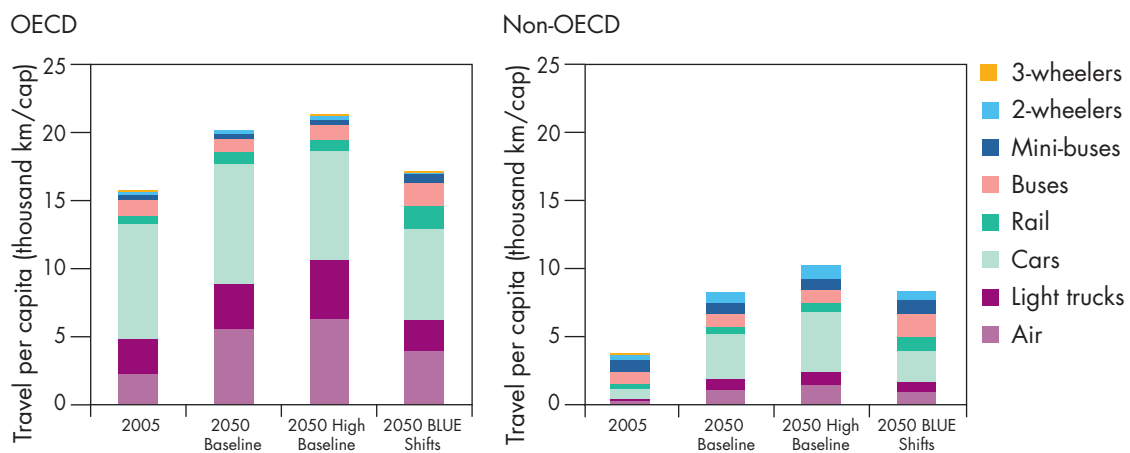
In addition:

- The BLUE Shift scenario recognises that, given the trends in the Baseline, it may not be feasible or reasonable to constrain travel growth by the same amount in all regions. The absolute level of travel per person, even in 2050, appears likely to remain far higher in OECD than non-OECD countries. Travel growth rates have been adjusted in the BLUE Shifts scenario so that travel per capita in all regions is set on a path that is eventually converging – some time after 2050.
- The tripling of total travel in non-OECD countries in the Baseline scenario is also assumed in the BLUE Shifts scenario, although with a different modal mix. The rationale for not reducing non-OECD travel in 2050 below the Baseline scenario is that this level, per capita, is still far below the average for OECD regions. Thus the set of assumptions used here is consistent with the eventual convergence of travel per capita in all world regions. Total travel in OECD countries, by contrast, is assumed to be 20% lower in 2050 compared to the Baseline scenario. As a result, total travel remains at or returns to about 2005 levels in the BLUE Shifts scenario instead of increasing by the 20% projected in the Baseline scenario. This reflects some replacement of travel with other mechanisms for achieving the same purpose, such as better land use leading to shorter trips, and the use of telematics for teleworking and videoconferencing.

- In the BLUE Shifts scenario, the projected growth in urban car travel, and proportionately even more significantly personal truck/SUV travel, is cut by between 30% and 100% (i.e. no growth), depending on region. Most of this reduced LDV travel is assumed to be shifted to more efficient modes, primarily bus and rail systems. The rest is assumed to shift to NMT or not to occur, e.g. through substitution by telework. For non-urban travel, the primary shifts are from LDV and air travel to rail and bus systems, along with travel reductions through substitution, e.g. with videoconferencing substituting for some air travel.
- Recognising that investments in better transit and inter-city transport systems may induce additional travel as more routes are served with better quality services, particularly in non-OECD countries, the BLUE Shifts scenario assumes for non-OECD regions an increase in urban passenger kilometres of travel by 2050 on rail and bus systems that is about 50% higher than the reduction in urban LDV travel. It also assumes that non-urban, including inter-city, rail and bus travel increase by about 25% more than the reduction in LDV and air travel. Thus, the scenario suggests a net mobility increase in non-OECD regions. In OECD countries, such an increase seems unlikely, especially in North America, given practical limits on the growth in the capacity of transit systems to absorb a large modal shift from LDV travel.

The BLUE Shifts scenario assumptions on this basis for OECD and non-OECD countries are shown in Figure 5.12. For OECD regions, passenger travel per capita in 2050 remains at (or returns to) its 2005 level, with a 20% cut compared to the Baseline scenario. The share of travel by rail and bus is much higher (doubling for rail and nearly doubling for buses), but cars, light trucks and air still dominate travel. In non-OECD countries, total travel per capita in 2050 remains close to the level in the Baseline scenario for 2050, but with significantly higher shares of travel by rail and bus, and slower growth in LDV and air travel.

Figure 5.12 ► Motorised travel per capita by scenario, OECD and non-OECD



Key point

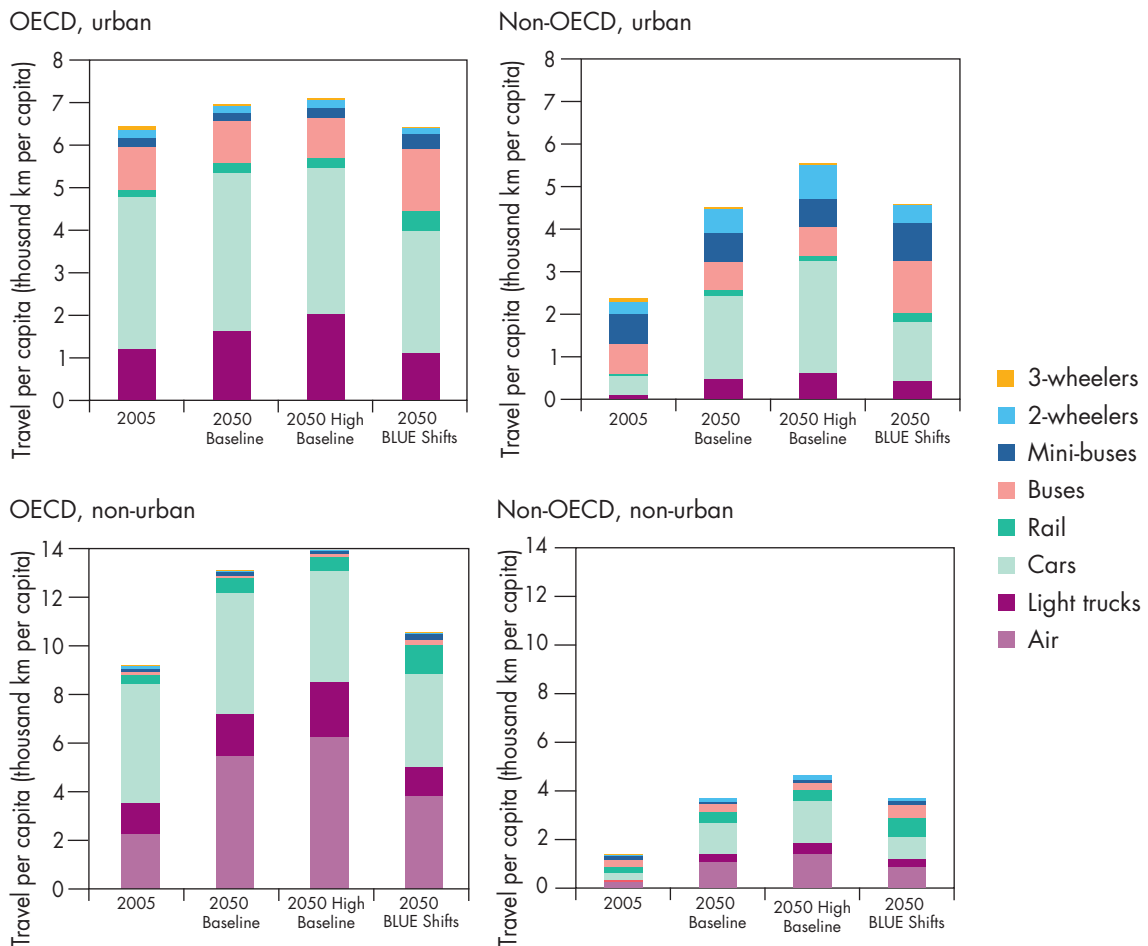
Rail and air travel are most likely to increase market share in OECD motorised passenger travel, but passenger LDVs will retain a significant market share and the OECD will not achieve as diverse a split of passenger transport modes as the non-OECD.

For some regions (especially Africa), total travel in the BLUE Shifts scenario is assumed to be higher than in the Baseline scenario due to the far more extensive bus and rail services available.

In urban areas, on the basis of the assumptions described earlier for separating out urban and non-urban travel, Figure 5.13 shows the per capita travel by scenario for OECD and non-OECD countries. In the Baseline scenario, urban travel per capita in OECD regions increases very slowly over time. The main difference in the High Baseline is a greater increase in the use of light-duty trucks. A much bigger change occurs in urban travel in non-OECD countries, where there is strong increase in travel by LDV in the Baseline scenario and even higher rates of growth in the High Baseline scenario.

In the BLUE Shifts scenario, compared to the Baseline scenario in 2050, travel on urban bus and rail increases from about 18% to 30% of all urban travel, and the

Figure 5.13 ► Urban and non-urban motorised travel per capita by scenario, OECD and non-OECD



Key point

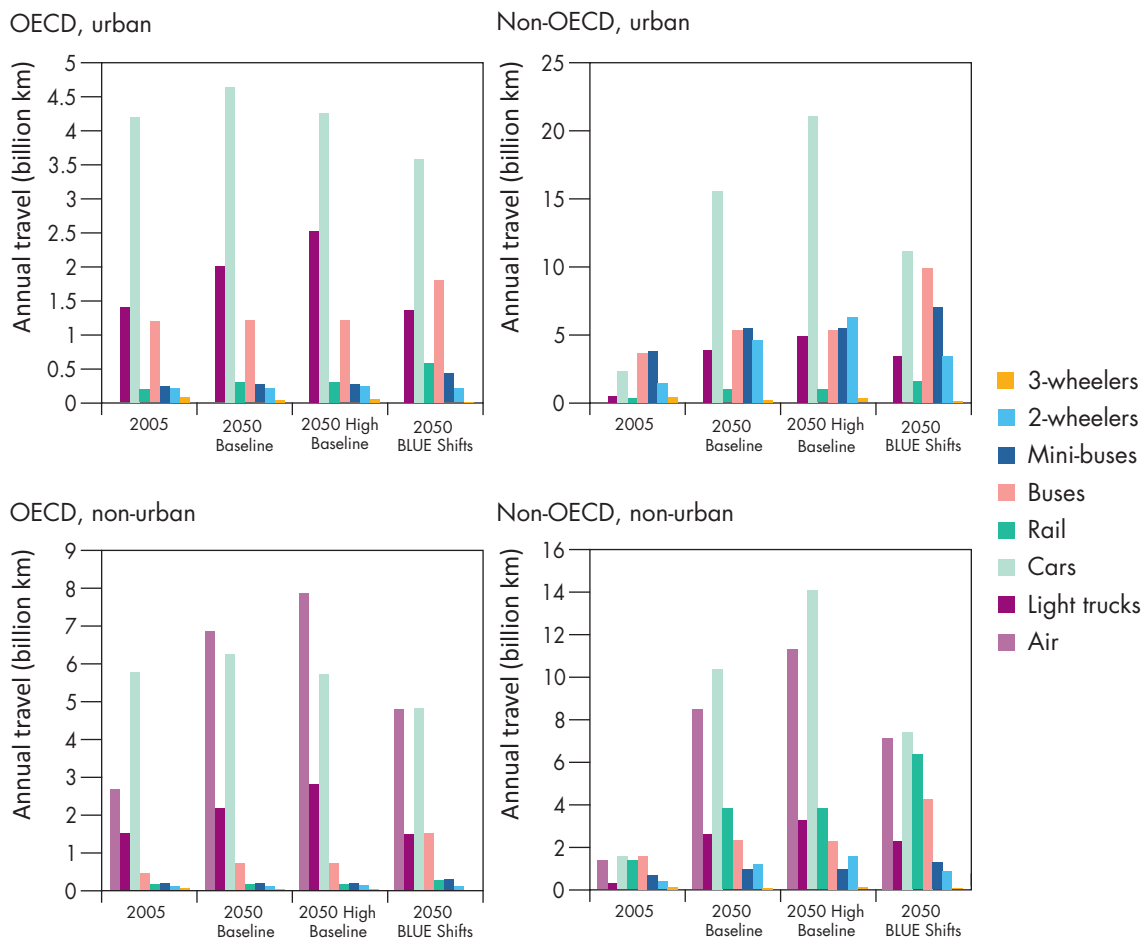
Per capita mobility in OECD countries decrease in BLUE Shifts, remains constant in non-OECD countries, compared to Baseline 2050.

share of LDV travel drops from about 72% to 60%. In non-OECD countries, urban travel by rail and bus drops from about 55% of all urban travel in 2005 to about 35% in the Baseline scenario in 2050, as people shift to personal vehicles. In the BLUE Shifts scenario urban travel by rail and bus retains over a 50% share as the shift to personal vehicles is significantly reduced.

For non-urban travel (Figure 5.13) in the Baseline scenario, air travel shows especially strong growth. This is cut considerably in the BLUE Shifts scenario. For non-OECD countries, the strong growth in LDV travel in the Baseline scenario is shifted significantly to long-distance bus and rail in the BLUE Shifts scenario.

Figure 5.14 shows the changes in travel patterns between the scenarios more clearly broken out by mode.

Figure 5.14 ► Total motorised travel by mode, scenario, OECD and non-OECD



Key point

Rail and road mass transportation is to gain market share in urban and non-urban areas, in particular thanks to high-speed trains.

In OECD countries:

- Urban rail travel in 2050 is nearly 100% higher in the BLUE Shifts scenario than in the Baseline scenario in 2005. Urban bus travel in 2050 is 50% higher in the BLUE Shifts scenario than in the Baseline scenario.
- The higher use of LDVs in urban travel from 2005 to 2050 in both the Baseline and High Baseline scenarios is reversed in the BLUE Shifts scenario. Light truck travel is 10% lower than in 2005 and car travel 20% lower than in 2005 in urban areas.
- For non-urban travel, growth in air travel is cut by half, *i.e.* it doubles in the BLUE Shifts scenario rather than tripling as it does in the Baseline scenario. A significant fraction of continental inter-city air travel is assured by rail links. Inter-city rail travel triples compared to 2005 and doubles compared to the Baseline scenario in 2050.

In non-OECD countries:

- Very rapid growth in urban car use, especially in the High Baseline scenario, is slowed in the BLUE Shifts scenario. Instead, urban bus and rail use increase by over 50%.
- For non-urban travel, the mode with the greatest share in the BLUE Shifts scenario becomes rail, assuming the rapid expansion of high-speed rail and regional rail systems. Bus travel also increases substantially, about doubling compared to the Baseline scenario. Air travel growth is cut from about 600% in the Baseline scenario to about 400% in the BLUE Shifts scenario in 2050.

Clearly, the BLUE Shifts scenario represents a dramatic departure from the business as usual case. At a minimum it would require a vast change in patterns of development and investment, away from road systems and private vehicles and toward collective modes of transport particularly, rail systems. The investment costs of BLUE Shifts are not estimated here but work of this sort could be done in the future to help better understand the relative costs and benefits of various scenarios.

Two-wheelers, buses and rail: a review of technologies to help achieve the BLUE Map/Shifts scenario

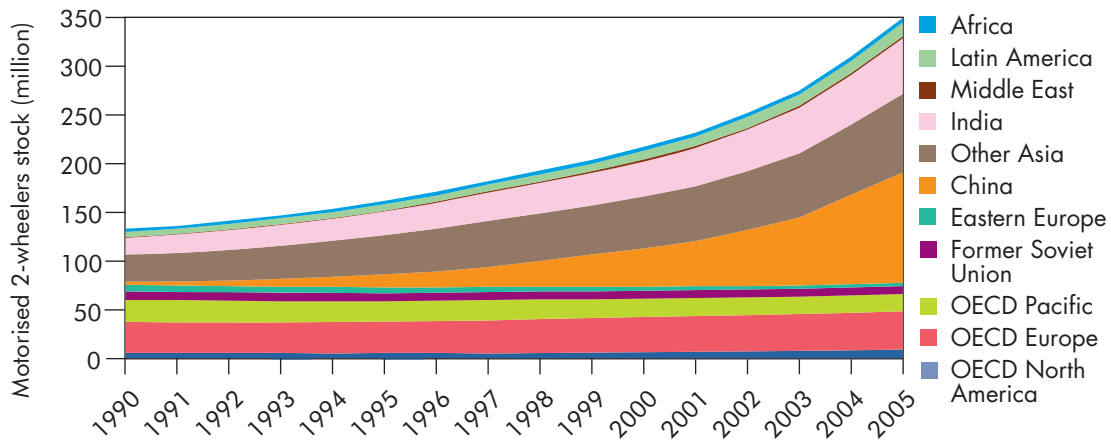
Analysis shows that people will shift their mode of travel to more efficient modes only if those modes are made more attractive and more cost-effective than the available alternatives. This is especially the case with bus and rail travel.

The BLUE Shifts scenario assumes no additional switching to motorised two-wheelers over and above that already included in the Baseline scenario. This section looks at the scope for some changes, such as the shift to a much greater use of electric two-wheelers as envisaged in the BLUE Map scenario, to help cut GHG emissions.

Powered two-wheelers

Powered two-wheelers, such as mopeds, scooters and motorcycles, are for many people, particularly in the rapidly developing countries of Asia, the first step to individual motorised mobility. Only later, as people become wealthier, they switch to LDVs. As a result, the number of motorised two-wheelers on the roads is growing rapidly, particularly in Asia (Figure 5.15). The total has almost tripled in 15 years, with even higher rates of increase in some parts of Asia.

Figure 5.15 ▶ Two-wheeler stock by region, 1990-2005



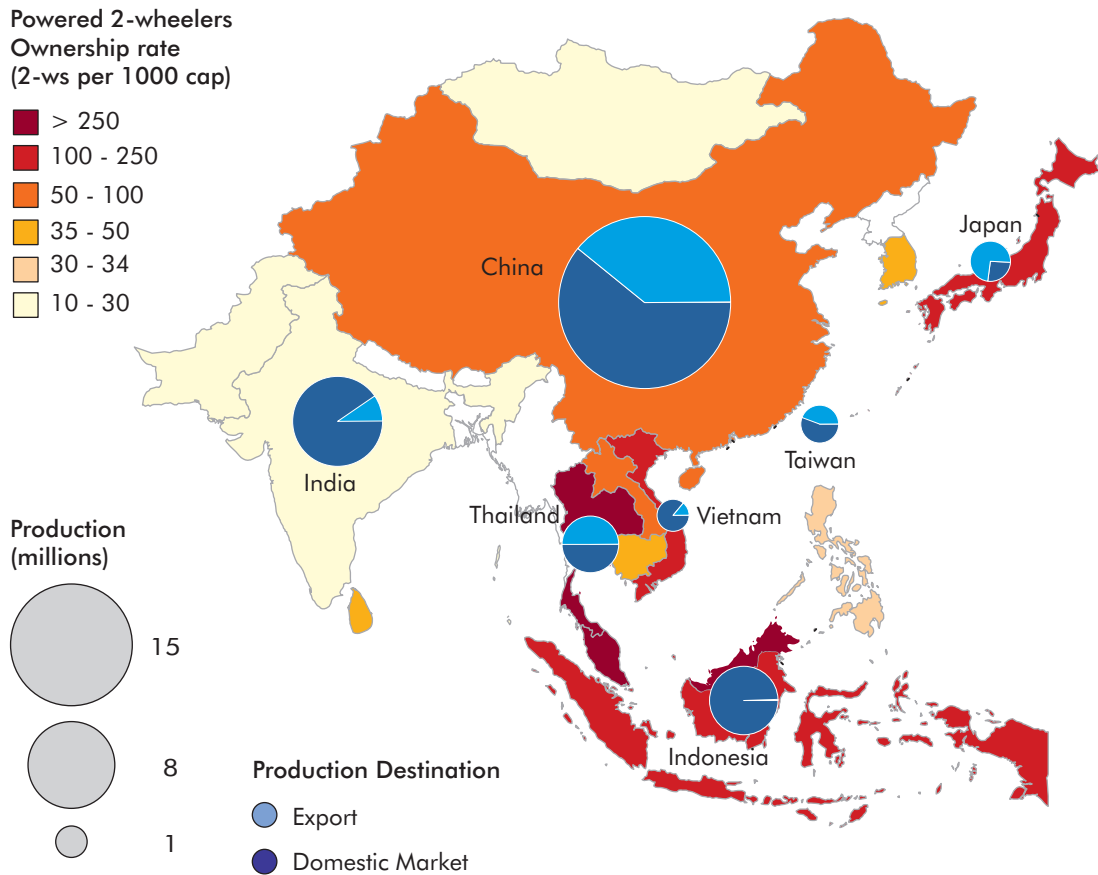
Source : IEA Mobility Model

Key point

Powered two-wheelers stock is growing very rapidly in Asia.

Although two-wheelers generally use only small amounts of fuel per kilometre, they contribute disproportionately to pollutant emissions, noise and accidents. They are also generally limited in range and in carrying capacity. Most of the world motorcycle fleet is powered by small (less than 125cc), often 2-stroke, engines due to their low cost of manufacture. Many are produced locally. Motorcycles powered by engines over 125cc are more popular in developed countries where incomes are higher, and are often used for longer distance trips and recreational activities. Recently, several manufacturers have begun offering three-wheelers with two wheels at the front, corresponding to essentially safer versions of two-wheelers. If successful, these vehicles may eventually make up a significant part of what is typically considered the two-wheeler market.

More than 95% of all two-wheelers are produced in China and Southeast Asia, which produce for local markets, and Japan, which mostly produces larger motorcycles for sale mainly in OECD countries (Figure 5.16). China produces 24 million two-wheelers per year, more than half of the total worldwide production of 47 million in 2007. Japanese total production has dropped by nearly 80% in the last 30 years, from a peak annual production of 7.4 million two-wheelers in 1981 to 1.6 million today, although Japan's production of larger motorcycles has remained almost constant in that period.

Figure 5.16 ► South-East Asia two-wheeler production and markets, 2007

The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source: World Motorcycle Facts and Figures, 2008.

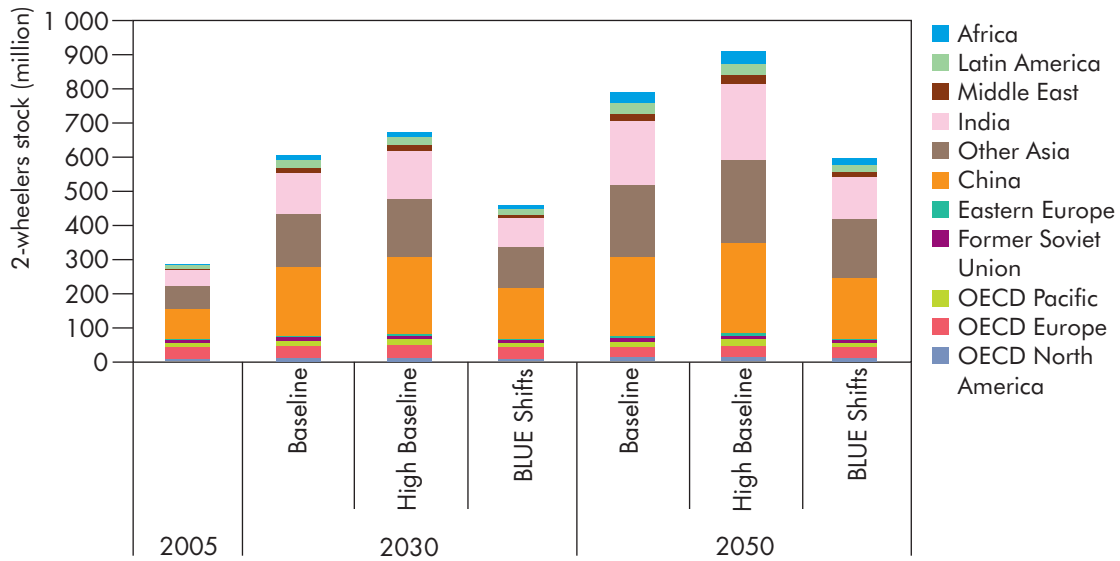
Key point

China is exporting more than 40% of its annual production.

In all scenarios, most of the forecast growth in two-wheeler stocks to 2050 is expected to occur in Asia. In the High Baseline scenario, stocks reach an even higher level than in the Baseline scenario. In the BLUE Shifts scenario, two-wheeler and three-wheeler ownership is assumed to be much lower than in the Baseline scenario, as more people shift to mass transit and non-motorised modes of travel. Even so, in the BLUE Shifts scenario, two-wheeler stocks in 2050 are double their 2005 levels.

Two-wheeler technology and efficiency prospects

There are few reliable data on the efficiency of motorised two-wheelers. In Asia nearly all of them run on gasoline, typically using between 1 Lge/100 km and 2 Lge/100 km. There is significant scope for two-wheelers to become more efficient, for example via engine friction reduction from using better lubricants, better combustion performance from using improved four-stroke engines, and optimising transmission systems. Hybridisation, using an engine and electric motor,

Figure 5.17 ▶ Two-wheeler stock projections by region, year and scenario**Key point**

In BLUE Shifts, the stock growth is limited thanks to efficient mass transportation systems in fast growing cities of Asia.

is also possible. The wider use of electric two-wheelers could also improve efficiency as well as eliminating petroleum use, cutting noise and eliminating pollutant emissions. Although few electric scooters exist today, over 15 million electric bicycles were sold in China in 2007 (Jamerson, 2009). There is scope to develop more powerful electric scooters.

Efficiency improvement is limited by characteristics of two-wheelers that will be difficult to change. These include:

- Although drag is not very important at the relatively slow speeds typical of the urban driving that dominates two-wheeler use (at least in Asia), the aerodynamic drag coefficient of two-wheelers is worse than that of cars. On the other hand, two-wheelers have a much smaller frontal profile. Aerodynamic drag can be reduced by adding fairings or other devices to reduce air turbulence around the motorcycle.
- Two-wheelers use tyres with friction levels per unit weight that are twice as high as those used on cars. It might be possible, through labelling or other measures, to encourage the purchase of more efficient tyres. But high friction levels are important for safety and should not be lowered if improved fuel efficiency requires such a compromise.

Hybrid two-wheelers

A number of ICE-electric hybrid two-wheeler models are being developed; some are already on the market. Most are from China (e.g. the Yiyong City Runner). At least one European manufacturer (Piaggio, 2009) is also preparing to launch a hybrid model.

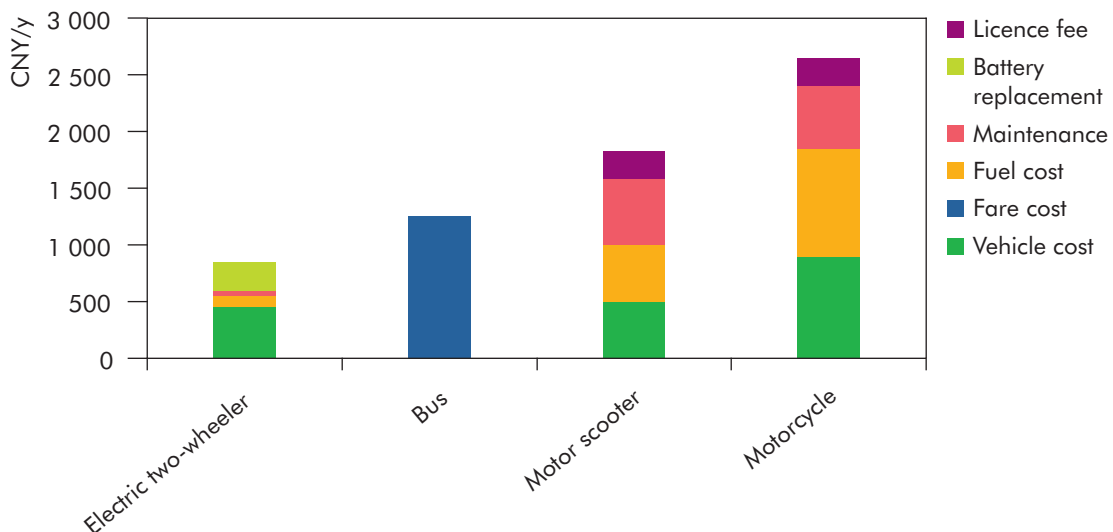
These ICE-electric models are typically configured to use the electric motor at lower speeds, using the engine for higher speeds and to recharge the batteries as necessary. European models may be configured to run in dual mode most of the time, but with an option to run only on the electric motor. Unlike cars, where the hybrid operation is triggered by power demand, on the first available hybrid two-wheelers, hybrid operation is triggered by speed. Hybrids may have a longer range than ICE only two-wheelers, typically 170 kilometres compared to 120 kilometres on Chinese models. However, hybrid two-wheelers are likely to be much more expensive than ICE-only equivalents, possibly by as much as 50%.

Electric scooters

Electric bicycles and electric low-power electric scooters are already very popular in China, due in part to a ban of gasoline-fuelled scooters in several big cities including Beijing and Shanghai since the mid-1990s. More than 10 million electric two-wheelers are now sold every year. Some cities are now banning them due to concerns over their number. They are usually powered by relatively small 200 to 600 W electric motors driven by lead-acid batteries making them the cheapest form of motorised transport in China (Figure 5.18).

To reduce pollution and noise, several cities in OECD countries, such as Paris, France and Austin, United States, are also starting to offer incentives for the purchase of electric two-wheelers.

Figure 5.18 ► Cost comparison of urban motorised modes in China



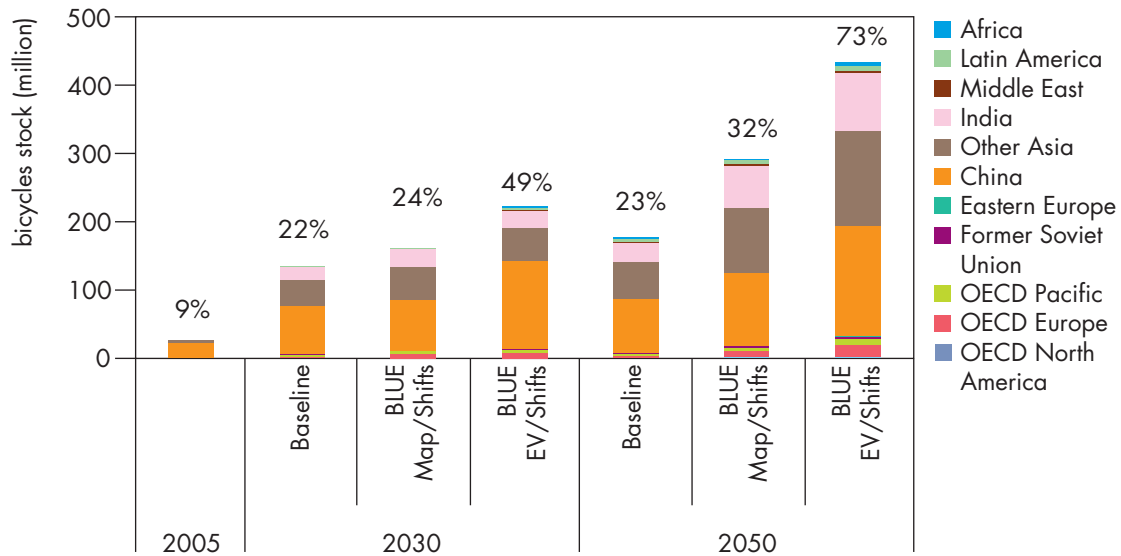
Source: Based on Weinert, 2006. As of June 2009, CNY 1.00 = USD 0.15.

Key point

Low maintenance cost and low-tax electricity makes the electric two-wheeler the cheapest motorised mode of transportation in China.

The number of electric two-wheelers is projected to rise rapidly in all scenarios, becoming an increasingly substantial share of the stock of all two-wheelers, especially in China and Southeast Asia (Figure 5.19). By 2050, electric two-wheelers are projected to represent between 25% and 75% of the worldwide stock of motorised two-wheelers, helped in part by expected reductions in the cost of batteries. The share increases in China and Southeast Asian countries are driven by policies restricting the use of ICE two-wheelers in dense urban areas.

Figure 5.19 ► Electric two-wheelers stock evolution and share, by region



Source : IEA Mobility Model.

Key point

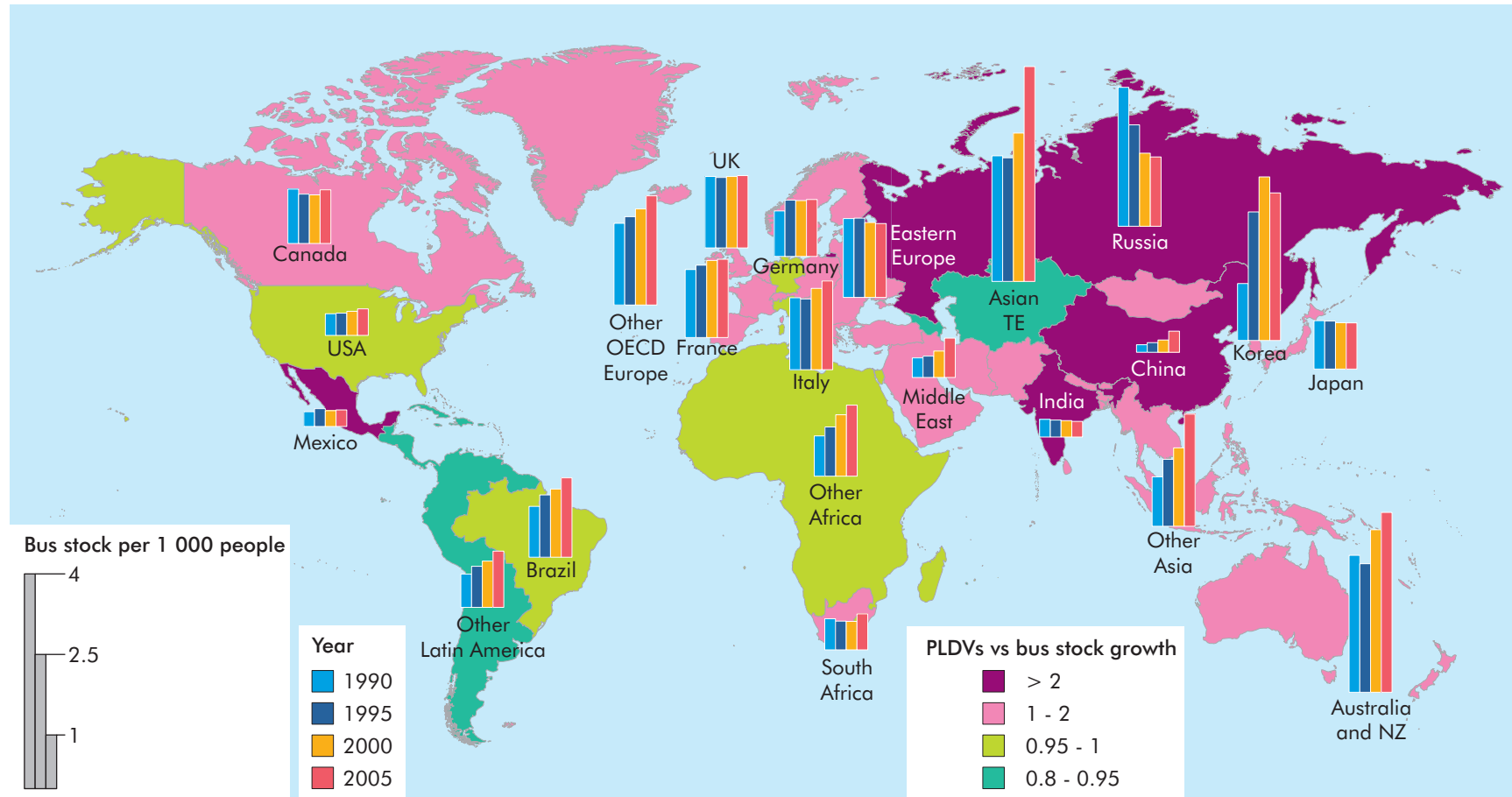
In BLUE EV/Shifts, electric two-wheelers reach three-quarters of the worldwide powered two-wheelers stock.

Buses

Bus travel constitutes an important share of all motorised passenger travel in many countries. Although there are far fewer buses on the roads than cars, they carry relatively large numbers of people, often over very long distances. Data are poor, but it appears that buses carry more passengers per year than urban rail systems in all but a few cities in the world. They still carry more people than cars carry in most developing country towns and cities.

These patterns may be changing. As has already happened in most OECD countries, bus travel is declining in many large cities in the developing world as car ownership rises. Figure 5.20 shows the rate of bus stock growth by region and the relative growth of bus stocks as compared to the growth in LDV stocks. Regions where bus stocks have increased faster or about at the same pace as LDV stocks since 1990 are coloured green; areas where the LDV stock has grown much faster than bus stocks are coloured red. Latin America has seen strong bus

Figure 5.20 ► Bus stock and LDV stock evolution 1990-2005



The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Sources: Various, including MoMo estimates; some regions include mini-buses.

Key point

In most of regions, growing stock of buses is over-shadowed by faster growing passenger LDV stock.

growth, including coaches and mini buses, in part due to a decline in rail services. In contrast, most of Asia was characterised by slow growth, if any, in buses while car ownership has increased rapidly.

Buses are very efficient in terms of fuel used per passenger-kilometre. Even at half or one third capacity, buses typically use far less fuel per passenger-kilometre than cars. Bus operators have a strong incentive to cut fuel costs. A bus operating for ten hours per day at 20 km per hour, working 300 days per year, travels 60 000 km per year. Such a bus might use 40 L of fuel per 100 km, or 24 000 L per year. This would result in a fuel cost of USD 12 000 at a USD 0.50/L fuel price. Particularly in the developing world, this can be a substantial part of the annual costs of owning and operating a bus.

Available data suggests that about 85% of bus sales worldwide are diesel-engine powered. Most of the remainder are gasoline powered. In a few countries, a small number are CNG powered. The comfort and safety of buses has improved considerably in recent years, as the quality of used buses imported into developing countries has improved and as more purpose-built buses are being manufactured in the developing world.

The fuel efficiency of buses appears generally to be improving, although new buses tend to be larger, with more powerful engines. Improvements in powertrains are likely to be the biggest source of further efficiency improvements. Light weighting can also play a role, along with better components such as tyres and more efficient air-conditioning systems. Aerodynamic improvements are also possible, although for urban buses that operate at fairly low speeds, this will play only a minor role. Although the boxy shape of most inter-city coaches could be improved, manufacturing costs and internal space optimisation seem to limit the potential for radical changes in body styles.

Urban buses

Nearly all large urban buses run on diesel fuel. Many urban buses are run by fleet operators with dedicated fuel stations and maintenance teams. Many operators have experimented with a variety of alternative fuels. Municipal bus operators often have strong public stakeholder involvement and are committed to using cleaner fuels and lowering emissions. As a result, fuels such as biodiesel, CNG, electricity and hydrogen are all in use in test or mainstream applications in bus systems around the world.

In the developing world, urban transport tends to depend on larger numbers of smaller buses than in OECD countries. Mini-buses with 12 or 15 seats are the primary mode of public transport in many cities, especially in Africa and parts of Latin America. Many of these buses are operated by private companies or individuals, with little co-ordination of bus services or of vehicle/fuel standards. Increasing bus sizes, and improving service frequency and quality can increase passenger numbers with a very significant impact on average fuel use per passenger-km, both for the bus system and the urban area more generally (IEA, 2002). The potential for buses to reduce overall fuel use by encouraging passengers to shift from cars and mini-buses to larger urban buses is a central element of the BLUE Shifts scenario.

Inter-urban buses

Inter-urban buses drive mostly on motorways in fairly steady conditions over long distances, unlike urban buses that stop frequently and have slow average speeds. Worldwide, inter-urban buses appear to have constituted around 20% of all bus sales in 2005 (UITP, 2007). Long-distance buses use commercial refuelling services along motorways and need to be capable of travelling long distances between refuelling stops. Technologies that limit vehicle range (such as battery electric drives or fuel cells) are likely to be better adapted to urban buses than to inter-urban travel. Hybrid systems may also be more suitable for urban buses, given the stop-and-go driving cycle. Efficiency improvements such as aerodynamics, weight reduction and low rolling-resistance tyres are likely to have more of an impact on long-distance buses than on urban buses.

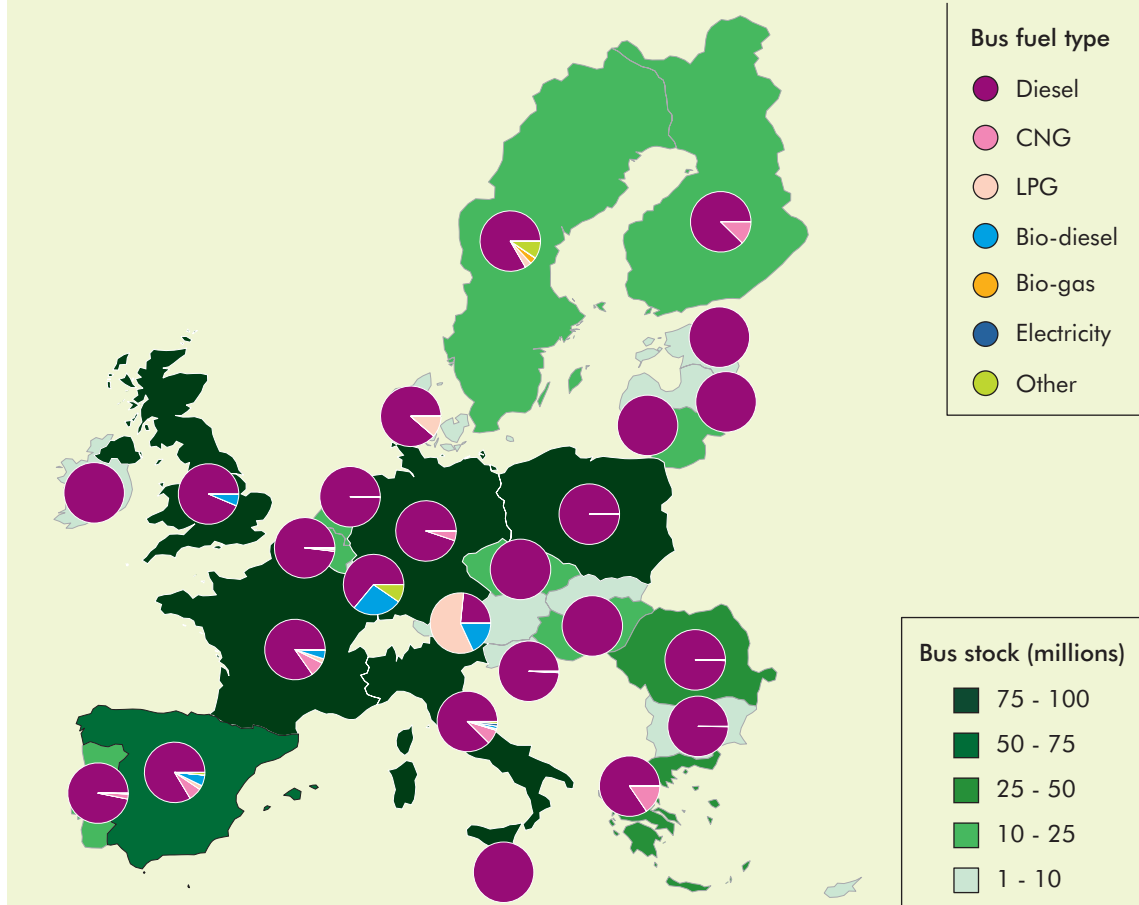
Heavy investment in rail, especially high-speed rail (HSR), infrastructures and services could limit or reduce future growth in long-distance bus travel. Countries such as France that have invested significantly in HSR have relatively low shares of long-distance bus travel. The BLUE Shifts scenario assumes that long-distance bus travel, and HSR and other inter-city rail travel all about double compared to the baseline, together absorbing much of the projected reduction in personal vehicle inter-urban travel.

Alternative fuel performance and potential

Urban buses in particular drive in densely populated environments where the health impacts of emissions can be high. In the last 20 years, considerable effort has been focused on reducing the emissions of local air pollutants from buses by introducing very low-sulphur fuels, cutting emissions of NO_x , hydrocarbons, sulphates and particulates, and enabling the use of better catalysts in particle filters to help cut emissions even further. Alternative fuels such as natural gas can also play a useful role in reducing emissions, although these options have proven to be relatively expensive. They have also been rendered unnecessary as clean diesel fuels with tailpipe controls have already successfully significantly reduced emissions. Alternative fuels continue to receive attention for their potential to reduce GHG and, in some countries, for fuel price or fuel security reasons. For example, in India and Bangladesh a growing number of buses run on natural gas both for air quality reasons and because large quantities of natural gas are available much more cheaply than diesel fuel.

Box 5.1 ► **The European urban bus fleet**

In Europe, most urban buses are powered by diesel engines. Natural gas and LPG engines in some countries have significant market shares due to local interest. As shown in Figure 5.21, non-diesel fuels are used most widely in Western Europe and constitute up to one-third of all fuel used in the urban bus fleet. In Austria, more than half of its fleet runs on LPG. Eastern European countries rely heavily on diesel to power their urban bus fleet. Trolley buses running on electricity are still marginal in the European Union.

Figure 5.21 ► Bus stock and urban bus fuel type in Europe, 2005

The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source : UITP, IEA Mobility Model.

Key point

Despite many alternative fuel experiments, urban bus fleet widely relies on diesel fuel in Europe.

Alternative fuels are used in bus transport to differing extents in different parts of the world:

Compressed natural gas (CNG): CNG buses have been in operation for many years in some cities such as Paris, New York and Los Angeles. Most manufacturers offer CNG versions of their buses. Placing CNG tanks on bus roofs appears to have worked well and allowed buses to have sufficient range without compromising passenger space. The public acceptance of CNG buses has been good. The technology can be considered mature for public transport. For gas-rich regions or countries, CNG-powered buses may offer the best alternative to diesel buses on cost and environmental grounds.

Water emulsion: emulsifying water into fuel can enable improved combustion by increasing oxygen levels. This can lead to small fuel savings and reductions in pollutant emissions such as NO_x. This approach has been used on some older buses as an interim measure to meet emissions standards, but it has rarely been used in newer buses.

Biofuel blends: conventional oil-seed biodiesel decreases the range of vehicles since it has 10% less energy per unit volume than petroleum diesel. Oil-seed biodiesel can be blended 10% to 20% with petrochemical diesel with little engine and exhaust system modifications, and has been used unblended in trucks and buses in a number of countries. Advanced biodiesel such as BTL and hydrogenated vegetable oil, could replace petroleum diesel in any proportion, eliminating all issues due to compatibility. BTL also has very significant potential to cut CO₂ emissions.

Hybrid buses

Hybridisation is particularly well suited to urban buses, given their typical duty cycles. Most manufacturers have prototypes under development and some are already producing small volumes of hybrids. Hybrids seem likely to penetrate the market rapidly in coming years, especially if fuel prices are high. But hybrids are expensive, up to 50% more than conventional buses. Although this differential should decline as volumes increase, hybrids are likely to remain very expensive in the near term in the developing world. A natural progression for bus technologies is likely to start with a move to cleaner diesels, then possibly progressively hybrids, plug-in hybrids and electric buses, with fuel cell buses as a possible long-term goal (IEA, 2002).

Box 5.2 ► Hybrid bus testing in the United States

The US DOE and the National Renewable Energy Laboratory (NREL) have undertaken hybrid bus evaluations in co-operation with various municipal bus fleets across the United States. This has included projects in New York, King County (Seattle), Knoxville and Indianapolis.

The projects have tested very large articulated hybridised buses, and have shown that maintenance costs have gone down as technology has improved. Fuel economy has significantly improved compared to earlier hybrids and compared to conventional diesel buses (Table 5.3). These tests suggest that hybrid bus technologies have matured and are technically ready for widespread introduction into urban bus fleets.

Table 5.3 ► Municipal articulated hybrid bus tests in the United States

	2002		2006		
	NYCT	NYCT	King County	Knoxville	Indianapolis
Fuel economy (MPG)	2.6	3.2	3.2	3.2	4.4
Fuel economy (L/100km)	90	73	73	73	53
% improvement over diesel reference	10%	30%	27%	-	-
Miles driven per vehicle over 12 months	17 500	28 000	37 000	5 000	8 000
Maintenance cost per mile covered (USD/mile)	1.50	1.23	0.44	0.62	0.66

Source: DOE, 2009.

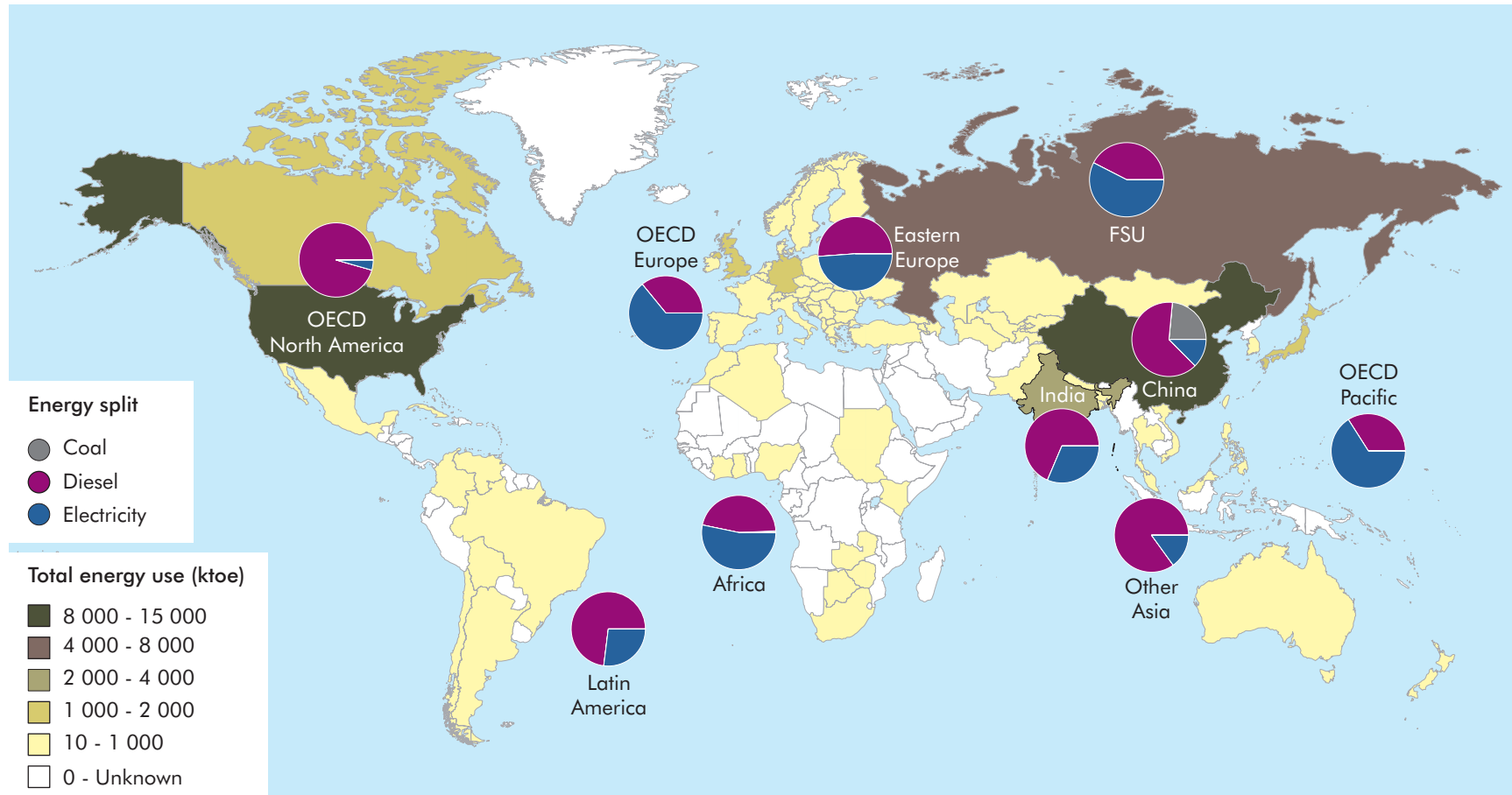
Plug-in hybrid and electric buses

Plug-in hybrids are not likely to be as useful in an urban bus context as they are for LDVs since urban buses may operate for 12 to 18 hours per day and travel 200 km to 400 km without recharging opportunities. If a bus is configured to run on its plug-in power for, say, 50 km, this may provide only 25% or less of the energy it needs, while it must carry around the heavy load of batteries for the entire day.

But if electrification can be provided for part of the bus route, plug-ins may work well. For example, if overhead electric lines are provided, say in a central business district, buses could recharge their batteries while they were operating on direct current so that they could rely on their batteries for more peripheral parts of their routing, as in San Francisco, Vancouver and Beijing. Such an approach may make the most sense in terms of the return on investment where many buses, which may cover several bus operators, share the same corridors. This model could also support electric buses if their battery power was sufficient to cover route sectors that were not grid connected. Some tramways already run partly on batteries for a few hundred metres in cities such as Nice and Bordeaux. This enables a reduction in overhead electricity infrastructure provision. Using plug-ins or battery-electric buses in conjunction with power lines also increases the reliability of the system, enabling it to continue to run if the grid is interrupted, for example, which is a concern in many cities and countries.

Electric trolley buses with overhead power lines have been running for decades without the need for energy storage on board. The trolley bus market share worldwide has decreased over the past decade. They may regain popularity as air quality standards in city centres tighten and liquid energy prices increase, although the cost of the overhead wiring and related infrastructure can be high.

Figure 5.22 ► Total rail sector energy use and energy sources, 2006



The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source: IEA Statistics.

Key point

China and the United States have an energy-intensive rail sector, mainly dedicated to freight transportation that depends largely on fossil fuel.

Rail

Many countries are making plans to expand their HSR systems and adopting policies designed to encourage rail travel. Against this background, passenger rail travel looks likely to grow rapidly in the future. Rail is already one of the most energy efficient modes of travel, but the industry continues to seek ways of improving the efficiency of its trains and infrastructure.

Energy use in the rail sector

The amount of energy used in rail transport in different countries, and the relative sources of that energy, varies widely (Figure 5.22). The United States and China, which use most energy on rail transport, are dominated by freight rather than passenger transport and mainly rely on diesel fuel. Worldwide, electricity is gaining share, rising from 17% of rail sector energy use in 1990 to 31% in 2006.

Reducing the energy used in rail travel will depend on the introduction of more efficient rolling stock, modernising infrastructures and optimising operations. Reducing GHG emissions will depend both on improving efficiency and, even more so, on the carbon content of the source of the primary energy used. A large share of passenger rail urban and inter-urban transport in most countries is already electrified. The progressive further electrification of rail systems, coupled with a shift towards low-GHG electricity generation, can ensure that rail achieves extremely low levels of CO₂ emission.

Urban rail

Urban passenger rail systems take a number of forms, including underground metro systems, surface light rail transit (LRT) systems, trams and heavier gauge commuter rail systems. A large number of projects are under way around the world to construct or improve existing urban rail systems (Table 5.4).

Table 5.4 ► Metro and LRT/Tram projects planned and under way by region

Region	Rail system type		Total
	Metro	LRT / Tram	
OECD Europe	25	62	87
OECD North America	5	12	17
OECD Pacific	1	3	4
Africa		3	3
Other Asia	3	4	7
China	5		5
Eastern Europe	2		2
India	4		4

Table 5.4 ► **Metro and LRT/Tram projects planned and under way by region**
(continued)

Region	Rail system type		Total
	Metro	LRT / Tram	
Latin America	3	2	5
Middle East	1	3	4
Russia	1	1	2
Grand Total	50	90	140

Source: Railway-Technology.com.

Most urban rail systems are powered by electricity. Electric motors are very efficient, so improving them will be challenging. As urban rail rolling stock is frequently accelerating or decelerating, reducing its weight is one of the most important ways of improving efficiency. Using regenerative braking devices will also help reduce energy needs.

High-speed rail

New high-speed (HSR) systems are being built or are planned in a number of countries (Box 5.3). HSR systems have already achieved some efficiency improvements with lighter trains and new car designs enabling larger capacities. Current technologies are some 15% more efficient than the previous generation of high-speed train (Alstom 2009). But energy use increases with speed and with the steeper gradients that are in some cases accepted in order to reduce rail infrastructure costs, for example to avoid tunnelling. If trends in this direction continue, HSR energy efficiency may decline in the future.

Box 5.3 ► High-speed rail development

More than 75% of the current HSR infrastructure is in five countries: Japan, France, Spain, Germany and Italy. New or planned projects around the world could more than triple the existing infrastructure by 2020 (Table 5.5). But most of these projects were announced before the recent economic crisis and some might be delayed or cancelled as a result of it.

Table 5.5 ► **High-speed rail lines existing or planned, by country**
(kilometres of track)

	In operation	Under construction	Planned	Total
Europe				
Belgium	137	72	0	209
France	1 872	299	2 616	4 787

Table 5.5 ► High-speed rail lines existing or planned, by country
(kilometres of track) (continued)

	In operation	Under construction	Planned	Total
Germany	1 285	378	670	2 333
Italy	744	132	395	1 271
The Netherlands	0	120	0	120
Poland	0	0	712	712
Portugal	0	0	1 006	1 006
Rusia	0	0	650	650
Spain	1 599	2 219	1 702	5 520
Sweden	0	0	750	750
Switzerland	35	72	0	107
United Kingdom	113	0	0	113
Total Europe	5 785	3 292	8 501	17 578
Asia				
China	947	3 289	4 075	8 311
Chinese Taipei	345	0	0	345
India	0	0	495	495
Iran	0	0	475	475
Japan	2 452	590	583	3 625
Saudi Arabia	0	0	550	550
Korea	330	82	0	412
Turkey	0	745	1 679	2 424
Total Asia	4 074	4 706	7 857	16 637
Other countries				
Morocco	0	0	680	680
Argentina	0	0	315	315
Brazil	0	0	500	500
United States	362	0	900	1 262
Total other countries	362	0	2 395	2 757
Total World	10 221	7 998	18 753	36 972

Source: UIC, 2009.

Note: The Official Chinese Mid. and Long-Term Network Plan (2004) states a final objective of 12 000 km of passenger high-speed rail network over 250 km/h.

Fuel options for rail

Once rail systems are already electrified, the options to improve efficiency by fuel switching are very limited. The focus needs to be on switching from diesel power to electricity, where it makes economic sense to do so. Electrification can be much more cost-effective, as long as more than five to ten trains per day use a given line (Alstom, 2008).

Where rail systems are not electrified, the hybridisation of diesel-powered trains can also help to reduce fuel consumption and pollutant emissions, especially when the trains are stopped in stations or travelling in urban areas, since a significant amount of energy is wasted by idling diesel engines when a train is stopped. A transition step towards full electrification might be to equip station platforms or urban areas with electric networks to which hybrid trains can easily connect. Larger battery packs and regenerative braking could further reduce diesel use in hybrid trains.

The major challenge for the rail industry is to power trains with clean, low-GHG electricity. The decarbonisation of electricity generation will be particularly important in this respect.

Achieving the BLUE Shifts scenario

If the modal shifts implicit in the BLUE Shifts scenario are to be achieved, a range of policies will need to be put in place, particularly to curb the future growth in personal motorised vehicle travel. These policies will need to be defined in such a way as to encourage shifting from one mode to another, or discourage shifting that would otherwise occur, while preserving and enhancing the benefits of mobility and access that people require.

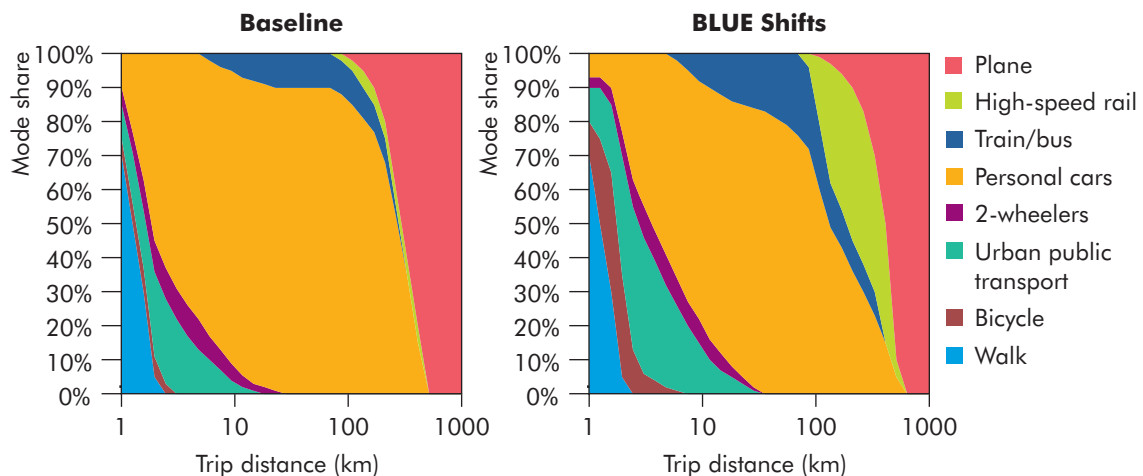
Some policies will incentivise positive changes in behaviour by providing new or enhanced low-impact travel options or reducing the need for travel e.g. through the wider use of videoconferencing. Other policies can be designed to discourage inefficient travel or the use of inefficient modes, through regulation, through price mechanisms or in other ways. Experience has shown that the combination of different approaches is needed to achieve a substantial and lasting impact. For example, when the cost of driving is increased through higher fuel taxes or road user charges, simultaneous investments are made in alternatives to driving such as improved bus or rail services. The earmarking of new transport tax revenues to pay for better public transit services has proven effective and politically popular in many countries.

The rate of shifting to a set of outcomes such as those envisaged in the BLUE Shifts scenario will depend on local and national circumstances, and on the stringency of the policy measures applied. This analysis does not seek to assess the political feasibility of different options. Rather, it focuses on the range of policy measures available and the way in which particular packages of policies might affect travel.

Travel changes by trip distance

Within all the scenarios, total travel comprises a mix of travel distances from very short trips to very long trips. Much better data would be needed to undertake a systematic treatment of modal shares and total travel by trip distance for each region. But Figure 5.23 provides an indicative look at how mode shares might typically look in 2050 in the Baseline scenario, which envisages the continuation of existing and already planned policy changes. This is compared with a set of outcomes driven by policies designed to achieve a lower CO₂ and in a more efficient system, such as that envisaged in the BLUE Shifts scenario.

Figure 5.23 ► 2050 indicative modal shares by trip distance for the Baseline and BLUE Shifts scenarios



Key point

Reliance on energy-intensive modes can be reduced by progressively substituting short- and long-distance trips with more efficient modes such as cycling or surface mass transportation.

Travel by LDV can be replaced or avoided both for short trips and long trips, although LDV may remain the most sensible mode of travel for intermediate trips of 10 km to 50 km. For short trips under 10 km, LDVs can often be replaced by other modes such as public transport, cycling or walking. For trips over 50 km, bus or rail services could play a bigger role than they do today. Over 100 km, HSR starts to show significant advantages. Over 1 000 km, air travel is likely to be the mode of choice for those who can afford it.

Urban policies

Urban and metropolitan environments are complex and often well established in terms of land use. Changing the pattern of land use in such circumstances can be difficult, and often appears inequitable, leading to winners and losers. Stimulating change usually needs strong political will. Urban change also usually requires long-term, sustained effort.

Most of the policies analysed here are not primarily designed to reduce GHG emissions but to achieve other policy goals. There is an extensive literature on designing, implementing and measuring the impact of transport policies from the perspective of these policy goals. Table 5.6 assesses the benefits of a range of policy outcomes in terms of their impact both on reducing GHG emissions and on other co-benefits. Urban travel policies have a broader impact than most vehicle or fuel technology-oriented policies, and are typically motivated for reasons other than energy savings or reducing CO₂ emissions.

The present analysis seeks to evaluate policy options with particular attention to their energy reduction and GHG mitigation potentials. Mode shifting primarily results in energy and GHG reductions from reductions in travel using less efficient modes, and increases in travel in more efficient modes. For LDVs, a reduction in travel can be reflected in three ways: lower car stocks, lower travel per vehicle and higher load factors per trip.

Table 5.6 ► Co-benefits: the impacts of different types of transport policy/technology

	CO ₂ reduction potential	CO ₂ reduction cost – effectiveness	Mobility/ access/ equity improvement	Air quality improvement	Traffic congestion reduction	Noise reduction	Safety improvement
Travel reduction/ modal shift	Medium-high	Variable and uncertain	Medium-high	Medium-high	Medium-high	Variable	Medium-high
Fuel economy improvement	Medium-high	Medium-high	None	Low	None	None	None
Electric / fuel cell vehicles	Variable	Low-medium	None	High	None	High	None
Biofuels	Variable	Variable	None	Low	None	None	None

Non-urban policies

Long-distance passenger travel offers relatively little opportunity for shifting to lower impact modes, except in shifting from cars to buses or rail travel, and from air to high-speed rail. Few countries have attempted to achieve such modal shifts. Efforts in Japan, France and other European countries to develop HSR systems are perhaps the best known and most successful ones. In many developing countries, buses still constitute the largest proportion of long-distance travel. To encourage more sustainable travel in the long term, policies will need to maintain and improve such bus systems, or convert them into high quality rail systems over time, thereby discouraging passengers from switching to car travel.

Other policy approaches can dampen long-distance travel demand. Virtual mobility can, for example, be encouraged by improved information and communication technologies. The long-term impact of such measures is uncertain; however, an increase in global interconnectivity could help spur increased demand for long-

distance travel. Another possible approach is to increase the price, for example through taxes and tolls, for air travel and long-distance car travel.

A review of policies to help achieve the BLUE Shifts scenario

There are a number of ways in which policy can influence the total amount and type of travel, as well as the relative use of different travel modes. These range from enhancing positive options such as public transit to penalising inefficient options such as single-occupant driving. To reduce demand for LDVs for urban travel, the following policies are reviewed in this chapter:

- Land use planning to increase density and mixed-use development.
- Promoting teleworking and other information-based substitutes for travel.
- Parking supply and pricing.
- Encouraging car sharing.
- Road pricing.
- Improving bus transit systems.
- Encouraging NMT such as cycling and walking.

To encourage reductions in air travel and LDV use for long-distance travel, rail and bus options are also reviewed.

This is not intended to represent an exhaustive analysis of policies and measures to encourage modal shift. Rather, it seeks to provide a sense of the types of measures available and their possible impacts.

Land-use planning

In cities, land use and transportation are closely tied to each other. The links between the two are complex and it is not always clear how to optimise one to get the most out of the other. Altering land-use patterns can have a direct effect on transportation patterns, and vice versa. For example, the development of a metro system can lead to much denser land-use patterns around the stations.

Land use can affect transport in a number of ways. These effects can be illustrated by a range of metrics, including: per capita motor vehicle ownership and use in terms of vehicle trips and distance travelled; mode splits in terms of the proportion of trips or travel by different modes including walking, cycling, driving, ride-sharing and public transit; and measures of accessibility by people who are physically or economically disadvantaged. A reasonable goal is to arrange land use and spatial structures to meet people's needs for access for mobility while minimising vehicle travel, traffic congestion, accidents, energy use, CO₂ emissions and other negative consequences.

The clearest differences in the effect of land-use patterns on travel can be seen by comparing urban core areas with inner and outer suburban areas. Table 5.7 shows the results of a recent survey in the United States. Very clear differences can be seen in terms of car ownership, the number of potential destinations that are close to home, and the typical use of different modes of travel.

Table 5.7 ► **Survey results of travel patterns in the United States by residential location**

	Urban	Inner suburb	Outer suburb
Cars per household	1.3	1.8	2.2
Number of destinations within 1 km	44.3	26.2	12.9
Mean distance to closest retail (km)	0.6	1.5	2.1
Non-auto modes used previous week			
■ Walked to work	33%	4%	2%
■ Walked to do errands	47%	20%	12%
■ Cycled	44%	24%	24%
■ Used transit	45%	12%	5%

Source: Horning, El-Geneidy and Krizek, 2008.

Similar differences in travel patterns may be found in a wide range of cities around the world, although the specific circumstances will vary from case to case. Once built, the stock of buildings and infrastructure in an area may take decades to change significantly. Changing land use is likely to be a slow process.

Even so, many cities and metropolitan areas around the world, especially in many non-OECD countries, are expanding rapidly. The development of such cities will be strongly influenced by local land-use policies and by other forces such as incomes and fuel prices. In OECD countries, new approaches to developing new areas, such as “smart growth” and “new urbanist” approaches (Katz, 1994), can produce newly developed areas that have the mixed-use characteristics of towns rather than those of subdivisions with tracts of car-dependent residences, significantly separated from commerce offices and schools.

Land-use factors affecting transport

Much has been written on the relationships between land use and travel. Litman (2008) reviews much of the recent literature and identifies a number of urban design factors that can affect traffic activity. These are set out in Table 5.8, including estimates, based largely on United States studies, reporting average or typical impacts from changes in different aspects of land use on vehicle and non-vehicle travel.

Although it is difficult to gauge how all these different factors might combine and what net impacts they might have, based on estimates for specific elements it seems

Table 5.8 ► **Urban design factors affecting traffic activity**

Factor definition	Definition	Travel impacts
Density	People or jobs per unit of land area (e.g. hectare)	Increased density => lower vehicle travel. Each 10% increase in urban densities typically reduces per capita vehicle kilometres of travel by 1% to 3%.
Mix	Degree that related land uses (housing, commercial) are located together. Sometimes measured as jobs/housing balance, the ratio of jobs and residents in an area	Increased land-use mix => lower vehicle travel and increase use of alternative modes, particularly walking for errands. Neighbourhoods with good land-use mix typically have 5% to 15% lower vehicle km of travel per capita.
Regional accessibility	Location of development relative to regional urban centre. Often measured as the number of jobs accessible within a certain travel time (e.g. 30 minutes)	Improved accessibility => lower vehicle travel. Residents of more central neighbourhoods typically drive 10% to 30% fewer vehicle kilometres than urban fringe residents.
Centeredness	Portion of commercial, employment and other activities in major activity centres	Greater centeredness => reduced vehicle travel and increased use of alternative commute modes. Typically 30% to 60% of commuters to major commercial centres use alternative (non-personal vehicle) modes, compared with 5% to 15% of commuters to dispersed locations.
Connectivity	Degree that roads and paths are connected and allow direct travel between destinations. Also relates to connectivity with transit systems and bicycle routes for easy transfers.	Improved connectivity => reduced vehicle travel, and improved walkway/cycle route/transit station connectivity tends to increase use of these modes.
Roadway design and management	Scale and design of streets, and how various uses are managed to control traffic speeds and favour different modes and activities.	Reduction in car-orientation (e.g. more multi-modal oriented streets) => increased use of alternative modes. Traffic calming measures that reduce vehicle speeds tend to reduce vehicle travel and increase walking and cycling.
Parking supply and management	Number of parking spaces per building unit or hectare, and the degree to which they are priced and regulated for efficiency.	Reduced parking supply, increased parking pricing and implementation of other parking management strategies => reduced vehicle ownership, trips and travel. Cost recovery pricing (charging users directly for parking facilities) typically reduces automobile trips by 10% to 30%.
Walking and cycling conditions	Quality of walking and cycling transport conditions and infrastructure, including the quantity and quality of sidewalks, crosswalks, paths and bicycle lanes and the level of pedestrian security	Improved walking and cycling conditions => increased NMT and reduced automobile travel. Residents of more walkable communities typically walk 2-4 times as much and drive 5% to 15% less than if they lived in more automobile-dependent communities.
Transit quality and accessibility	The quality of transit service and the degree to which destinations are accessible by quality public transit in an area	Improved transit service => increased ridership and reduced automobile trips. Residents of transit oriented neighbourhoods tend to own 10% to 30% fewer vehicles, drive 10% to 30% fewer miles, and use alternative modes two to ten times more frequently than residents of automobile-oriented communities.

Table 5.8 ► **Urban design factors affecting traffic activity** (continued)

Factor definition	Definition	Travel impacts
Site design	The layout and design of buildings and public spaces	More pedestrian friendly and multi-modal site design => reduced automobile trips, particularly if implemented with improved transit services.
Mobility management	Various programmes and strategies that encourage more efficient travel patterns. Also called "Transportation Demand Management" (TDM).	Mobility management => reduced vehicle travel for affected trips. Vehicle travel reductions of 10% to 30% are achievable through comprehensive TDM programmes.

Source: Adapted from Litman, 2008.

reasonable to conclude that in many cities and metropolitan areas a comprehensive approach could, over time, cut vehicle travel by substantial amounts. Ewing and Cervero (2001) conclude that the effects of increasing density and accessibility can lead to potential reductions in the number of trips by over 10% and in kilometres of vehicle travel by over 30%.

Public transport needs a reasonably dense population in order to be effective. Cost-effective urban bus systems typically depend on a minimum density of 25 dwellings per hectare (dw/ha) (Banister, 2008). Due to its higher capacity, LRT needs at least 60 dw/ha. For comparison, the city of Paris has now an overall average of 150 dw/ha.

Reorganising an existing city can take years. Some aspects can be expensive, although where new development is planned much can be achieved by re-routing planned investments, for example by converting tract development into a mixed-use development. In the long run, net infrastructure costs may even be negative since a city with more cycling and walking infrastructure, and less roadway space, could be cheaper to build and maintain than one dominated by roads. The provision of walking and cycling infrastructure is amongst the least expensive elements in changing land-use and transport patterns.

Box 5.4 ► **Cities from scratch**

This box outlines three recent examples of new sustainable cities that are now being developed.

Dongtan, China

In conjunction with the planned Shanghai Expo in 2010, China is building its first eco-city, Dongtan, on an island on the delta of the Yangtze River. In 2010, it will house 25 000 inhabitants, in a design from a British consultant company which is intended to be sustainable in terms of its building stock and its transportation system, as well as waste management and other key aspects.

The first phase of Dongtan Eco-City is conceived as a town consisting of three villages, each with its own distinct character. The city will then continue to grow as a collection of towns connected by cycle routes and public transport corridors, allowing inhabitants access to different parts of the city by tram, bus, bicycle and on foot. The aim is that people will take no more than seven minutes to walk from any part of the city to a bus or tram stop. Dongtan's design is based on the principle that all its citizens can be in close contact with green open spaces, lakes and canals. Its buildings will be highly energy efficient, and the city will be largely powered by renewable energy.

Most of Dongtan's waste output will be recycled and composted. The bulk of its organic wastes will be returned to the local farmland to help assure its long-term fertility and its capacity to produce much of the city's food needs. Existing local farming and fishing communities will have significant new business opportunities at Dongtan, enhancing the island's long-term environmental sustainability (WBCSD, 2009; ARUP, 2009).

Two projects in the UAE

The city of Masdar, Abu-Dhabi, under development in the United Arab Emirates (UAE), aims to rely only on renewable energy and will be car-free and energy independent. It is being constructed beside Abu Dhabi's international airport and should welcome its first inhabitants by the end of 2009. The city will be developed in phases, with plans for 50 000 people to eventually live in this 6.4 km² area (<http://www.masdaruae.com>).

A project in neighbouring Dubai will attempt to recreate the structure and atmosphere of Lyon, France, with elements of its public transport system. The 300 to 400 hectare scheme, estimated to cost EUR 500 million, will be located either in an urban area near the Burj Dubai tower or in the desert near the Emirates' planned second international airport (<http://www.arabianbusiness.com/507583-french-city-lyon-to-be-rebuilt-in-dubai>).

Cities such as these may not only provide sustainable transport and living for their residents, but may also inspire other cities and countries around the world to undertake similar "sustainable cities from scratch" initiatives.

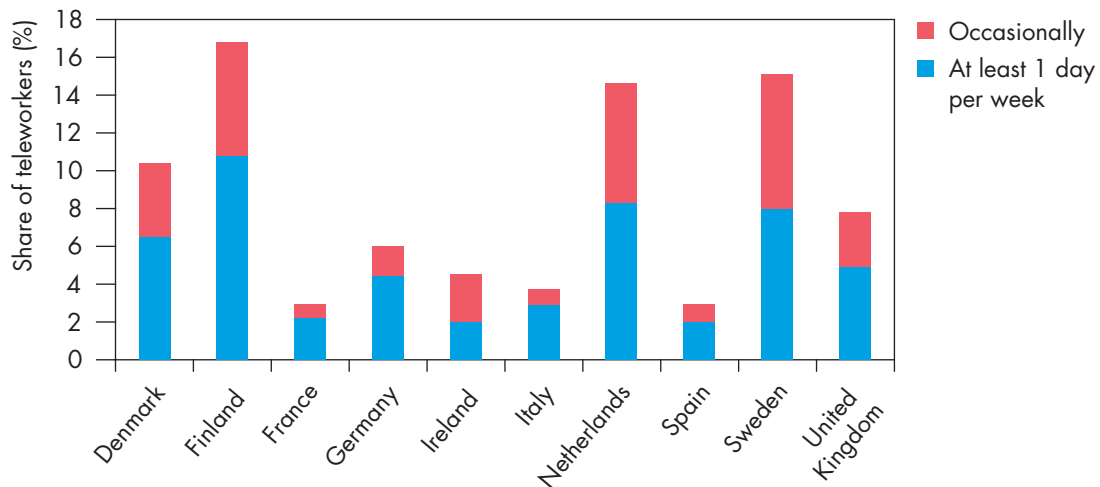
Telework

Telework or telecommuting refers to work that is undertaken outside the conventional workplace using information and communication technologies. There is considerable literature on the advantages and drawbacks of telecommuting, and on its potential impacts on travel.

Telework first became a realistic prospect for some workers in the 1990s, and many research projects were undertaken to study it. The most recent set of comprehensive estimates of telework levels, in Europe in 1999, (Figure 5.24) shows two distinct groups of teleworkers, those who regularly telework at least one day per week either as an employee or on a self-employed basis, and more occasional teleworkers who telework less than one day per week on average. The variance in the incidence of teleworking by country is quite high,

with more than 10% of workers in the Nordic countries and the Netherlands teleworking on an occasional or regular basis, compared with fewer than 4% of workers in Italy, France and Spain. This report found that the variation was affected both by the size of the share of information workers within each country and by the social acceptability of teleworking.

Figure 5.24 ▶ European telework shares by country, 1999



Source: European Telework Association, 1999.

Key point

Northern European countries are more proactive towards teleworking.

A more recent study in Norway (Hjorthol and Nossun, 2008) found that although about 40% of employees occasionally work from home, only 9% of them can be seen as regular teleworkers. Regular Norwegian teleworkers were found to work from home between 1.3 and 3.8 days per month. Recent estimates for the United States (Cox, 2009) indicate that only about 4% of the population work at home full time, but nearly 23% work at home at least one day per month.

Telework and travel

Reducing daily commuting to and from the workplace is often seen as one of the most important potential gains from teleworking. In theory, if an entire workforce teleworked one day per week, a country's commuting-related vehicle travel could be cut by 20%. However, the reality is more complex and the potential travel reductions are probably more limited. The interconnections between changing traditional working patterns and transportation demand are related not only to the direct commute but also to the ways in which teleworking changes other aspects of lifestyle, for example non-work travel and choices of residential location. It can also affect energy use within buildings, for example leading to higher energy use at residences during days of work at home.

Although most studies find that the direct travel reduction from telework is proportional to the number of commuting trips reduced and the average trip length, a number of studies have found that this direct impact is significantly offset by increases in other travel and/or that telework has not had a major impact on aggregate travel. Hjorthol and Nossun (2008) found little evidence that Norwegian teleworking leads to less travel, concluding that it could in fact lead to more travel because of higher flexibility, increasing urban sprawl and changing travel patterns. Muhammad *et al.* (2007) found that teleworking in the Netherlands enables people to live further from their offices, making fewer but longer commuting journeys on those days they travel to work. Choo *et al.* (2004) examined the impact of telework on travel in the United States over the period 1966 to 1999, concluding that telework led to about 1% less travel in total over the time period.

More work is needed to better understand how different types of telework may affect travel, if policies are to encourage teleworking as a means of reducing travel levels. In the absence of such information, it would be risky to rely on teleworking as a significant means of reducing travel levels, although it may, in combination with other policies such as road pricing or other strategies to discourage vehicle travel, provide an important alternative to travel to help make other policies more effective.

More needs to be done also to identify which policies might promote the most travel-saving forms of telework. Governments have a range of instruments at their disposal, including:

- Collecting and analysing data on telework and its various impacts on a systematic, on-going basis and reporting on what works best.
- Identifying and widely disseminating information and case studies on successful strategies to encourage teleworking
- Ensuring that national or local regulations do not prevent or inhibit beneficial forms of telework.
- Investing in telecommunications infrastructure such as broadband networks that enable teleworking.
- Ensuring that the marginal cost of vehicle travel is relatively high, both to encourage telework and to reduce the likelihood of an increase in non-commuting travel associated with telework.

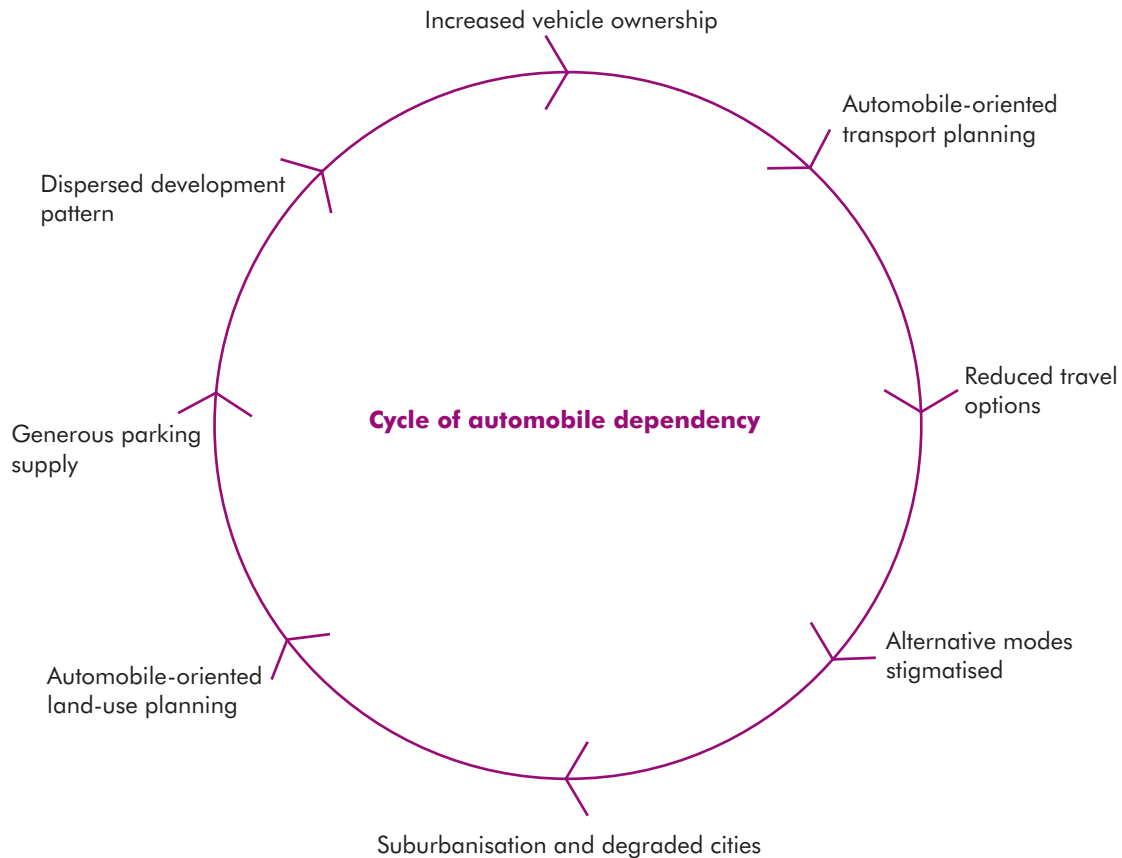
In the developing world, where the number of information workers is low but rising rapidly, raising the awareness of telework as a viable alternative to commuting, and exploring the social and energy impacts of telework, should be priorities in the near term. The integration of policies supportive of telework into more comprehensive transport strategies may be a particularly useful medium-term approach. The promotion of tele-shopping, and teleconferencing for businesses, and the use of telematics for other distance-based activities, should also be explored.

Parking policies

Parking is an essential component of the vehicle transportation system. Typically, a car is parked around 23 hours every day, and uses several different parking spaces

each week. Ample parking encourages car ownership and driving in cities, even where good quality public transit is also available. Parking can also encourage sprawl as space is needed for parking lots. Litman (2008b) observed a “cycle of automobile dependency”, to which ample parking supply contributes (Figure 5.25). Policies influencing parking supply and costs can reduce traffic and the use of cars for urban travel.

Figure 5.25 ► Cycle of automobile dependency



Source: Adapted from Litman (2008b).

Key point

The space occupied by the personal automobile is no longer sustainable in dense urban areas.

Parking-related policies for reducing driving can take a wide range of forms, from limiting the number of spaces to establishing pricing or tax policies such as charging for parking at public spaces or levying taxes on privately offered spaces. Reducing the number of spaces within an area or entire municipality can be done by converting public spaces to another purpose. For example, approximately 3 000 road parking spaces in Paris were converted to Velib bicycle stands during 2006-08.

It is difficult to measure the impacts of a parking policy in isolation from other policies. Parking policies are often undertaken in conjunction with other policies, for example an improvement in public transport or the Velib bicycle programme in Paris, so only combined impact estimates are available.

Box 5.5 ► **Some parking statistics**

- *Private cars are parked more than 90% of the time on average.*
- *In the United States, there are approximately three times as many parking spaces as vehicles in a typical urban environment.*
- *One parking space can occupy from 13 m² to 37 m², depending on the type of parking, and the necessity for access lanes.*
- *Taking into account the typical vehicle travel to and from a parking space, one parking space generates approximately 1t CO₂ to 3t CO₂ per year for private residential or professional parking; a public parking space generates approximately 4t CO₂ eq to 8t CO₂ eq per year.*

Sources: Cordis, 2002; Sareco, 2008

Parking policies need to be enforced if they are to be effective. When parking spaces are reduced, for example, there may initially be an increase competition for the remaining parking spaces and an increase in illegal parking. If illegal parking is controlled and parking becomes difficult to find, then users can be expected to eventually seek other travel modes, to share rides, or to reduce travel, roughly in proportion to the percentage reduction in available parking.

Cordis (2002) compiled a number of parking case studies (Box 5.6) that suggest the impacts of parking policies vary considerably depending on the city and country in which they are applied. Relatively similar policies, such as new pricing policies, appear to have had different impacts on traffic. In some cases, no significant modal shift occurred; in others, public transport use increased.

Box 5.6 ► **Parking case studies**

Utrecht, the Netherlands

In the mid-1980s, the city of Utrecht in the Netherlands implemented a set of measures to improve the air quality of the city centre and reduce car traffic. It included reforming the parking system and reallocating parking spaces, increasing parking charges and creating new traffic circulation patterns within the city centre. The public mass transport share of all travel increased from 42% to 52% and travel to the city centre by car was reduced by 15%.

Helsinki, Finland

A comprehensive set of policies has been in place in Helsinki, Finland, since the early 1980s, mixing parking policies and other policies aimed at reducing car use and ownership in the

city centre. Parking fees, resident parking permits, and park-and-ride initiatives have been implemented, together with a car-sharing programme. Surveys and related modelling work suggest that:

- Car drivers are willing to pay EUR 0.65 to get 100 m closer to their destination, or are ready for a three-minute search for a parking place in order to avoid a 200 m walk. Other studies have found that car drivers are willing to spend even longer to find a place as close as possible to their destination.
- Doubling parking costs decreases car mode share by about 20%.
- If parking costs are always at least the same as the public transport fare for regional trips up to about 40 km from the city centre, the share of car trips decreases by 8%.
- If the walking distance to and from a car is the same as that of a public transport alternative, the car mode share decreases by 13%.
- If all transit connections that include transfers are replaced by direct routes without transfer waiting and walking times, 10% of those car users that would have to make transfers if taking public transport (less than 20% of all respondents) would start to use public transport (thus, less than 2% overall).

These results relate to particular cities at particular points in time, but may indicate an order of magnitude that may be relevant to other cities, especially those having similar characteristics.

Source: Cordis (2002).

Parking supply

Parking supply can significantly influence vehicle travel. A regular survey held in 30 cities in France (Sareco, 2008) shows that 53% of parking spaces are for private personal use. Municipal on-street parking provides 32% of spaces and commercial areas, such as parking lots, provide 15% of spaces. In so far as this pattern is followed in other countries, it is clear that incentives for or requirements on the private sector must be part of an overall parking policy strategy.

Policy in many countries is inconsistent. For example, many municipalities make public parking relatively inaccessible through high fees or by limiting spaces, but at the same time allow or even encourage privately offered spaces to increase by requiring new apartments or office buildings to have a minimum private parking capacity. This can be counter-productive to wider efforts to reduce urban private travel or to increase its cost. There is also evidence that the further the car is parked away from the residence of the owner, the less the car is used (Sareco, 2008), suggesting that requiring residential parking to be located in designated areas rather than at or next to dwellings can play a part in strategies to reduce private vehicle travel.

Parking prices

The relationship between higher parking prices and driving levels can vary considerably depending on factors such as the policy context and location. For example, the use of resident-only parking helps to cut down on visitor or commuter parking in a neighbourhood, but may increase the incentive for residents to own a car. Conversely, even if public parking is priced, its availability can encourage more visitor or commuting travel into an area. Sareco (2008) estimates that publicly accessible parking spaces, such as commercial parking lots or on the street, generate much more CO₂ than private spaces, since a parking space that can be accessed by anyone has higher rotation, involving a greater number of vehicles coming and going from the urban centre. A balanced policy, with the provision of limited resident-only parking at a cost along with limited, priced, public parking, may make sense in many areas. Car-free zones can reduce car traffic within their areas by up to 100%, but have less impact overall within a city unless they are very widespread.

Some private parking operators, such as those in Zurich, Switzerland and Lyon, France, are experimenting with linking the price of parking to the number of entries/exits a car makes in a week. This allows a lower price for a limited number of entries, e.g. to cover daily commutes, but increases the charge above a given number per week to discourage car use for non-commuting, e.g. lunch or shopping trips.

Various parking policies have been tried in different cities and countries. Table 5.9 provides, for a range of documented policy studies, estimates of the typical impacts on car modal share, the cost of the policy and the time horizon of impacts.

Table 5.9 ► Parking measures - impacts on car use

Policy	Car share reduction potential*	Time horizon**
Resident (priced) parking permits (only works in dense cities)	Low	Short
Parking entry quotas (maximum entries per week); e.g. 25% of parking implementing entries quotas	Low	Short
Park and ride systems; e.g. sufficient parking so that 20% of people travelling in a corridor can commute through park and ride	Low	Medium
Parking "cash out" or other policies that lead to significantly cutting the number of parking spaces at a work place	Medium	Short
Laws limiting numbers of parking spaces for future developments	Medium	Long
Doubling parking charges across significant areas	Medium	Short
Doubling distances between residence and car park	Medium	Short
Car-free zones	High	Medium

Notes: * "Low" car travel reduction potential is around 0% to 10%, "medium" around 10% to 25%, and "high" over 25%.

** Including implementation. "Short" is around one to two years, "medium" two to five years, and "long" over five years to have full effect.

Source: Cordis, 2002; Sareco, 2008.

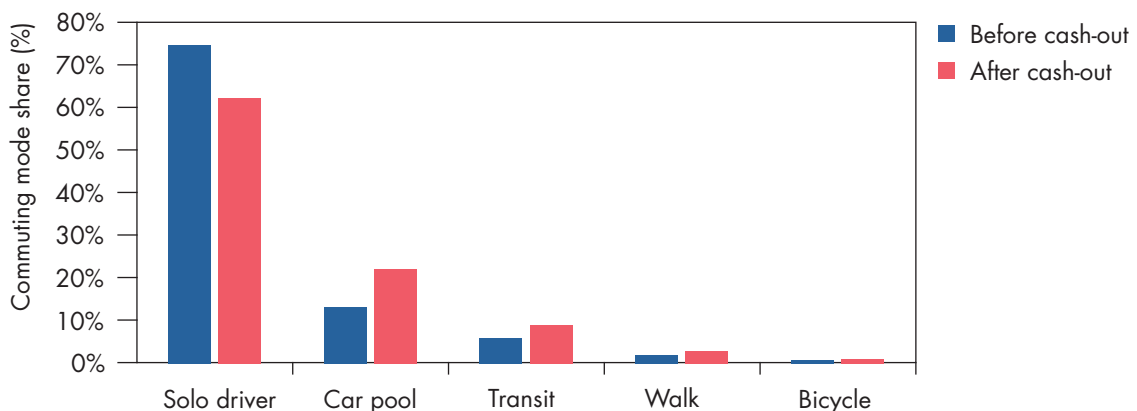
Parking policies can be implemented fairly quickly either alone or within other policy packages. Most parking policies oriented to reduce travel are found in dense cities where they may be most efficient. In suburban environments, where there are large amounts of provided and/or informal parking opportunities, it may be difficult to cut parking provision sufficiently to have any impact on driving. But even in such cases, cutting parking and imposing parking requirements can be an important part of a broader strategy towards land-use change and reducing vehicle travel.

Parking cash-out

In parking “cash-out” schemes, employers offer employees cash in lieu of free or subsidised parking. The best known example exists in California, where in 1992 the State enacted a parking cash-out law which set out to require companies (employing more than 50 people and located in an air basin designated “non-attainment” for an air quality standard) to adopt a parking cash-out scheme if they subsidised commuter parking in parking spaces they did not own. They could reduce the number of parking spaces they leased without penalty. The cash-out law requires such employers to offer employees the option of choosing between subsidised parking and the cash equivalent of the subsidy. Although the California law is quite limited in terms of application, and never became mandatory, a number of medium-sized businesses, together with parts of the California government, adopted schemes on similar lines.

Shoup (1997) conducted a survey of eight offices that adopted the policy to see what effects it had on commuting patterns. For all eight firms, a significant shift in patterns was seen comparing the pre-scheme and post-scheme data. The average percentage of solo driving dropped by between 2% and 22%. The maximum rate of solo driving pre-scheme was 88%; the maximum post-scheme rate was 78%. Average shifts in mode share across the eight firms are shown in Figure 5.26. The number of people commuting by means other than solo driving increased by about 50%, rising from 24% to 37% of the total. Average vehicle travel for those working at these firms fell by about 12%, equivalent to around 1 000 km per year per person.

Figure 5.26 ▶ Mode shifts from cash-out programmes in California



Source: Shoup, 1997.

Key point

Financial incentives can guide people towards sustainable mobility.

The cash out policy appears to have had quite significant impacts on travel in these organisations. This would not necessarily be the case in other firms or in other locations. A particular challenge would be to broaden the regulation to encompass also companies that own their own parking lots and allow free use of spaces. In such cases, it is likely that a companion regulation would be needed to require a minimum charge or value to be placed on all free parking as a basis for a cash-out programme.

Car-sharing systems

As opposed to car pooling, by which passengers share a ride in the same vehicle, car sharing involves individual drivers using a pool of vehicles on a shared basis. Formal and semi-formal car-sharing schemes have existed since the early 1960s in various municipalities. Until now, no scheme has ever been big enough to create a significant modal shift from individual vehicle owning to shared vehicle operation. But systems in many cities are growing rapidly, and car sharing could become important in the future in terms of lowering demand for private vehicle ownership and cutting total vehicle travel.

Typically, car-sharing systems seek, through providing convenient short-term rentals rather than ownership, to increase access to vehicles for those who do not own them, and to reduce the cost of accessing a car when one is needed. For participants who choose not to own their own car, the fixed costs associated with accessing vehicles drop dramatically, while the variable costs of vehicle use rise, as operators cover their fixed costs through time-based rates. By shifting costs to the margin on a pay-per-use basis, car sharing generally sends better market signals regarding the costs of driving compared to vehicle purchases that involve a one-time major investment followed by relatively low marginal costs per trip. This should tend to dampen car use. But if participants did not previously own a car or did not plan to own a car, joining a car-sharing programme is likely to increase their use of vehicles.

Car sharing requires users to be within convenient walking, cycling or public transport distance of where the vehicles are parked. As a result, almost every car-sharing initiative lies within city centres, although the vehicles are often used to make trips out of the urban area. This means that the service is typically offered where car ownership levels are already relatively low, and the opportunity to cut car ownership is likely to be less than in suburbs and rural areas. But in suburbs and rural areas, where ownership is high and there could be a larger potential to reduce it through car sharing, user densities are unlikely to be sufficient to successful schemes. Innovations to overcome such barriers, such as delivering cars to users' residences, might help expand car sharing but would also increase costs.

Ryden (2005) and Shaheen (2006) report that surveys in six European and three American cities show that car-sharing users reduce their annual vehicle travel by about 30% in Europe and by about 40% in the United States. Moses (2005) reports on car-sharing programmes in Bremen, Germany and in Belgium, and estimates the decrease in total car travel among different types of users, including those who have never owned a car, those who formerly have, and those who still own a car, as shown in Table 5.10.

Table 5.10 ► Car usage prior to and after subscribing to car-sharing schemes

	Prior to car-sharing (km/y)	When car-sharing (km/y)	Proportion of total users
Never car owners	0	1 000	25%
Former car owners	10 000	5 000	65%
Still car owners	10 000	9 000	10%
Average	7 500	4 400	100%

Source: Moses, 2005.

For the cities included in the study, each user reduced their car travel by about 3 000 km per year on average compared to their travel levels before joining the car-sharing scheme. At the time of the survey, the number of users was about 1 700, leading to 5.1 million vehicle km being saved every year.

Ryden (2005) found that those who shift from their own cars to car-share cars typically reduce the vehicle size and type, on average to a much more fuel efficient vehicle, and that two-thirds of the car distance saved is transferred to public transport. The rest is accounted for by travel reduction, walking and cycling.

Shaheen (2004) estimated the operational cost of running a car-sharing scheme at about USD 18 000 per vehicle per year. The cost of the vehicle travel, energy and CO₂ saved then mainly depends on the intensity of car usage, which in turn is related to the number of members per shared vehicle. Using various assumptions from these studies, the IEA has developed a first approximation of the CO₂ cost-effectiveness of car-sharing schemes, as shown in Table 5.11.

On these assumptions, these car-sharing schemes are estimated to save about 200 000 t CO₂ per year at an average saving of around USD 250 per t CO₂ saved, related mainly to the large savings of avoided car ownership. However, the cost saving per tonne of CO₂ varies significantly from one region to another, and depends heavily on the number of private vehicles reduced per shared vehicle. As a result, the United States shows a significant cost per tonne of CO₂ saved, mainly because only five vehicles are reduced per shared vehicle. If this were seven, as for Europe, the cost per tonne saved in the United States would also be negative.

The number of people participating in car-sharing schemes has increased by about 10% per year in recent years. Extrapolating this trend to 2050, the current 350 000 or so participants would grow to about 15 million, equivalent to 1% of people living in urban areas with more than 1 million inhabitants. Assuming a similar rate of participation in other regions, about 25 million people would be projected to participate worldwide in 2050. This may seem a large number, but it would remain a small share of the total population of such cities and is certainly within the realms of possibility.

Table 5.12 shows the impacts of such an outcome in 2050, assuming that participation rates reach 30 people per car in all regions. The number of avoided vehicles per shared vehicle is assumed to drop as regions become wealthier,

Table 5.11 ► Cost evaluation of car-sharing schemes, 2006

Region	Members (thousands)	Number of shared vehicles	Private vehicles reduced per shared vehicle	Travel reduction (km/y/user)	Members per vehicle	User cost per shared vehicle per year (USD)	Cost of alternative modes per km (USD)	Savings per year from saved vehicles (USD)	Total saving (USD mil)	Fuel savings (L/km)	Total fuel savings (million L)	CO ₂ reduction (kt)	Cost per tonne CO ₂ saved (USD/t CO ₂)
Europe	213	7 686	7	3 000	28	16 000	0.20	5 000	60.2	0.07	44.8	108	- 560
North America	118	3 337	5	4 000	35	16 000	0.20	6 000	16.3	0.09	42.4	102	- 160
Asia	16	608	8	3 000	26	12 000	0.15	4 000	7.4	0.06	2.8	7	- 1 095
Australia	1	65	9	3 000	17	16 000	0.20	6 000	2.0	0.08	0.3	1	- 3 097
Total / average	348	11 696		3 338	30	15 792	0.20	5 163	53.3	0.08	90.3	217	- 246

Source: IEA based on Shaheen (2004, 2006) and Ryden (2005).

Table 5.12 ► Potential savings in 2050 in car-sharing scenario

	Urban population in cities > 1 million (millions)	Total members (thousands)	Car-sharing vehicles (000s)	Number of vehicles saved per shared vehicle	Travel reduction (km/y/user)	Fuel savings (L/km)	Total Fuel savings (million L)	CO ₂ reduction (kt)	Cost per tonne CO ₂ saved (USD/t CO ₂)
Europe	156	1 638	54 600	6	3 000	0.06	295	708	- 150
North America	280	2 940	98 000	5	4 000	0.07	823	1 976	- 103
Asia	1 000	10 500	350 000	6	3 000	0.06	1,890	4 536	- 150
Australia	20	210	7 000	6	3 000	0.07	44	106	- 525
Rest of the world	1 000	10 500	350 000	6	3 000	0.06	1,890	4 536	- 150
Total	2 456	25 788	859 600				4,942	11 861	- 111

with North America remaining slightly below other regions. Avoided vehicles are assumed to be more efficient in 2050, reducing the per-vehicle fuel and CO₂ savings. The result is that about 75 billion km of vehicle travel could be avoided in 2050 along with 5 billion L of fuel and nearly 12 million t of CO₂. The cost per tonne of CO₂ saved would remain negative everywhere except in North America, assuming fewer vehicles are saved per shared vehicle in that region. If six vehicles could be saved per shared vehicle, North America would also achieve a negative cost per tonne of CO₂ saved.

Although this represents less than 2% of projected worldwide vehicle travel by 2050, car sharing would then be making a significant contribution to energy and CO₂ savings, and apparently with a realistic prospect of negative cost. So far, government policies have rarely been directed at supporting or increasing car-sharing schemes through, for example, supporting tax policies. Although at a city level, steps have been taken to enable such schemes, for example through providing on-street parking spaces for car-share vehicles. With more policy support, car sharing could potentially play a much larger role in 2050.

Road pricing

Road pricing⁴ has been implemented in several cities and on many vehicle routes in recent years. Usually, the main objective is to reduce traffic congestion, there lay reducing journey times and improving reliability for individual and mass transport users. It can also help make goods delivery operations more efficient. Other objectives are to raise revenue, for example to pay for specific infrastructure,⁵ to encourage modal shifts to public transport, and to reduce noise and pollution in city centres.

Existing urban systems

Existing road-pricing systems typically cover either a particular highway or highway network, or a defined city centre area. In city area systems, private vehicle owners have to pay to enter a restricted zone at specific times or daily. The charge is sometimes adjusted to be higher during periods of peak travel and likely congestion. Each system has its own specificities, which affect its performance and impacts.

The major city systems in operation include:

- **Singapore** implemented its congestion charging system in 1975, the first such urban charge system in the world. It initially used humans to check that vehicles complied with the system, but an automatic vehicle detection and payment system became fully operational in 1998. The system then became known as Electronic Road Pricing. The system works as a charged zone with a cordon ring, requiring vehicles to make a payment each time the cordon line is crossed. The system automatically deducts a balance from a pre-paid account, with devices in each vehicle that keep track of the driver's available balance.

4. Also known as road-user charging or congestion pricing.

5. Toll roads have been in existence since the Roman era in some parts of Europe.

- **London** launched its congestion charging scheme in 2003. It is a cordon zone system, which requires private vehicles entering the congestion charging zone to pay on a daily basis. The zone was expanded in 2007. The charge applies from 07:00 to 18:00 on weekdays. There is no charge at other times. Some types of vehicles, such as electric vehicles, are exempt from charges.
- **Stockholm** initiated a trial congestion tax scheme in 2006, with a cordon system covering a large part of the central urban area. As in London, revenues were used, in part, to expand the bus system. Park-and-ride lots were also added to key commuter corridors. In 2007, residents voted to make the system permanent.
- **Milan** has an “Ecopass” charging system in which high-emitting vehicles pay a charge to enter central Milan. Vehicles compliant with the EURO 3 emissions standard (or better) are exempt. Very high-polluting vehicles are banned from the city. The system is temporary, but a decision whether to extend the scheme beyond December 2009 will be made in 2009.

Table 5.13 ► Characteristics of several road-charging schemes

Town	Name	Date implemented	Scheme type	Area (km ²)	Operating hours	Price	Enforcement system
Singapore	Electronic road pricing	1975	Cordon ring (in)	7	Mo-Sa 7.00 - 22.00	Gantry / time dependent EUR 0 to 1.5	Radiofrequencies + cameras
London	Congestion charge	2003	Cordon ring (in)	40	Mo-Fr 7.00-18.30	Flat rate, GBP 8/day	CCTV cameras
Stockholm	Congestion tax	2006 (became permanent in 2007)	Cordon ring (in and out)	35	Mo-Fr 6.30-18.30	EUR 1 to 2/crossing depending on time of day	Laser + cameras
Milan	Ecopass	2008 (temporary through end of 2009; extension possible)	Cordon ring (in)	8	Mo-Fr 7.30-19.30	EUR 2 to 10/day	Digital cameras

Note: For scheme type, “in and out” means that in Stockholm the cordon ring requires payment for both entering and exiting.

Existing motorway systems

Road pricing has existed for centuries in the form of highway tolls. In recent years, some systems have been created that use electronic pricing systems, in order to avoid long lines of cars waiting at toll booths. Others have been converted to such systems. Some systems vary the charge by time of day or congestion conditions, making them true congestion pricing systems. Some systems charge more for truck travel than for lighter vehicles.

Two examples of such systems, both of which make extensive use of intelligent transport systems (ITS), are:

Toll collect – Germany: Germany introduced a GPS-based road tolling network in January 2005, focussed on road freight transport. At the end of 2007, the system covered more than 12 500 km of motorways split into nearly 5 400 separately charged sections, and 50 km of federal roads. Trucks with a gross weight over 12 tonnes have to pay charges according to the distance they drive on motorways, their emission class and their number of axles. By basing charges on the emission class of the vehicle, the system provides an incentive to switch to newer trucks meeting better emission standards. One reported impact is that the distances driven by empty trucks have decreased by 15%.

407ETR – Canada: this entirely electronic toll system covers a 108 km highway north of Toronto. Tolls for all types of vehicles are based on distance travelled. In February 2008, zone tolling was introduced with charges based on distance travelled, the zone, the time of day, the type of day (i.e. regular work day, holiday or weekend) and by vehicle class according to weight and size. The system features an advanced ITS system allowing electronic tolling with instant calculation of the appropriate toll. In 2008, about 77% of all trips were paid using transponders. It is reported that the zone tolling scheme prevents even the busiest part of the highway from being congested at rush hours.

Box 5.7 ► **Intelligent transport systems use in the German truck charging system**

Most road-pricing systems around the world now make use of advanced ITS to monitor vehicle traffic, collect tolls, and collect and provide other information about the system.

In the German Toll Collect highway system for trucks, charges are paid by means of a free-flow tolling system which avoids the need for physical toll booths. The system is triggered by a transponder or on-board unit (OBU) installed on the vehicle. If no transponder is detected, a back-up optical character recognition (OCR) system reads the vehicle's number plate and matches this to truck registration data. All motorway entry and exit points are equipped with a gantry for the OCR system.

Road charges can be prepaid and are charged automatically for vehicles with an OBU installed. The OBU calculates the truck's position and movement by means of GPS, and the charge is calculated and sent to a computing centre. The charge can also be prepaid manually at refuelling stations or via the internet, in which case compliance is by means of the OCR system. As of 2008, more than 600 000 Toll Collect OBUs were installed in trucks around Europe and 90% of all customers paid automatically.

In the near future, the system will be used to collect statistical information about traffic, which will be used for traffic management. Time and area dependent prices could be introduced to further moderate traffic levels and to avoid congestion. It may be possible to enlarge the system to all federal roads and to include cities. Concerns about data safety and the implications of the surveillance of all traffic activities remain to be addressed.

Impacts of congestion pricing

Road-pricing systems reduce congestion by cutting the amount of traffic and vehicle travel. They can also have a variety of other impacts. For London and Stockholm, studies have made detailed estimates of the various costs and benefits associated with the congestion charging systems (Transport for London, 2007; Transek, 2006). These evaluate such impacts as traffic reductions, emissions reductions, safety impacts and CO₂ emissions reductions. Clearly, reductions in any of these areas provide benefits to society. System costs have also been calculated.

Table 5.14 summarises estimates for the congestion charging schemes of London and Stockholm, with the following parameters:

- **Global socioeconomic cost (million EUR):** this covers all the costs and benefits derived from the installation of the congestion charge, *i.e.* amortising the investment, operational costs, money invested in mass transport to make modal shifts possible, toll charges, and monetisation of the time, noise, emissions, accidents and fatalities saved.
- **Direct costs (million EUR):** this covers only the cost of the congestion charge system, including amortising the investment, operational costs and costs due to the improvement of mass transit systems.
- **CO₂ emissions saved (in t CO₂ eq):** both schemes have led to a reduction of traffic activity at the scale of the whole city, implying fuel saved and CO₂ emissions reduced.
- **Cost per tonne of CO₂ saved (EUR/t CO₂ eq).**
- **Travel reductions (in million km):** this is the reduction in traffic activity due to the congestion charging scheme. From this data, it may be possible to estimate the likely impact on traffic reductions in other cities considering congestion pricing schemes.

Table 5.14 ► Costs and impacts of various congestion charge systems

City	Vehicle kilometre reduction (million km)	CO ₂ emissions reduction (t CO ₂ eq/year)	Direct cost for local authorities (million EUR)	Marginal cost from direct costs (EUR/t CO ₂ eq saved)	Global socio-economical cost (million EUR)	Marginal cost from global costs (EUR/t CO ₂ eq saved)
Stockholm	85	43 000	68	1 581	-38	-884
London	237	120 000	190	1 583	-124	-1 033

Sources: Transport for London, 2007; Transek, 2006.

The direct costs of both systems are significant – at EUR 68 million for Stockholm and EUR 190 million for London. But the estimated net socioeconomic costs are negative, indicating that when the benefits are taken into account these charging systems provide net benefits to society. So, although the direct cost at around EUR 1 500/t CO₂ saved is quite high relative to other CO₂ reduction options, the

whole cost from a societal point of view is of the order of minus EUR 1 000/t CO₂ saved. This suggests that cordon systems of congestion pricing within large urban areas provide important benefits to society. Their implementation should be driven by those wider benefits. CO₂ reduction should be seen as a co-benefit, rather than the main driver for such schemes.

The congestion charging schemes in Stockholm and London reduce average vehicle travel by around 40 km per resident per year, a relatively small share of total vehicle travel per capita. But these systems are quite small, covering only vehicles that cross into a defined zone in the centre of each city. Higher levels of vehicle travel could be replaced by these systems if they were expanded, e.g. by using multiple charging zones (which would create more cordon lines over which a crossing fee would be levied), expanding systems into suburbs, and expanding onto motor routes connecting cities, as long as good quality mass transit alternatives were available both within and between cities.

In 2006, Stockholm had a population of around 2 million people. London had about 8 million. Worldwide, about 1.2 billion people live in cities with more than 1 million people (City Mayors, 2009). In 2020, this figure is expected to grow to 1.5 billion and by 2050, it could reach 2.2 billion people, equivalent to 24% of the 9 billion population expected at that point. If half of those cities fully implemented a congestion charging scheme, such schemes would cover 1.1 billion people in 2050. If each scheme cut vehicle travel by 500 km per person, the total vehicle travel reduction would be 550 billion km. With more efficient vehicles in that year, and the increased use of mass transit (which uses some fuel), the net fuel savings would be on the order of 30 billion L or 80 million tonnes of CO₂ per year.⁶ Based on the London and Stockholm estimates of net societal benefits, these CO₂ reductions would have a negative cost.

Bus rapid transit

Bus rapid transit (BRT) is a term used to describe advanced bus systems such as those originally adopted in Curitiba, Brazil. These have been more recently adopted in Bogota, Colombia and a range of other cities in the developing world. BRT initiatives are now implemented or planned in over 40 cities, on all continents.

BRT systems employ a combination of features that greatly improve bus system performance compared to ordinary systems. These include:

- Dedicated bus corridors, physically separated from other traffic lanes.
- Modern bus stops that are more like stations, with pre-board ticketing and comfortable waiting areas.
- Multi-door buses that dock with bus stations to allow rapid boarding and alighting.

6. As for all modal shift policies, as LDVs become more efficient, the benefit of shifting in terms of fuel use and CO₂ declines, though other important benefits remain. The estimates here assume Baseline efficiency improvements.

- Large, high-capacity, comfortable buses, often meeting high-emission standards.
- Bus prioritisation at intersections either through signal priority or physical avoidance, for example through underpasses.
- Full transferability between buses within the system for a single fare.
- New, innovative approaches to bus service contracting and bus system management. (IEA, 2002).

CO₂ analysis of BRT systems

Wright and Fulton (2005), Blonn (2006), INE (2008) and others have found that BRT systems have achieved substantial reductions in car traffic as people move from personal vehicles to mass transit systems. Wright and Fulton developed generic scenarios for urban mobility in a reference case without BRT and then with combinations of BRT, better non-motorised transit infrastructure, and other changes superimposed. Assuming a 5% shift in urban mode share to BRT and a BRT cost of USD 2.5 million per km of construction, the net cost was estimated to be USD 66/t CO₂ eq reduced. These estimates are quite sensitive to various assumptions, especially the construction costs of the system. The authors also assumed that operating costs are fully paid for by fare revenues. These operating costs are assumed, therefore, to reflect the system benefits to consumers, and so are not counted as part of the cost of the CO₂ reduction.

The Bogota TransMilenio (TM) BRT system has become a reference for all developing cities. The Phase II expansion of the system has been approved for Clean Development Mechanism (CDM) funding by the United Nations Framework Convention on Climate Change (UNFCCC) under the Kyoto Protocol. In Phase I, TM users' travel times fell by 32%, particulate matter pollution fell by 9% in some areas of the city, and accident rates dropped by 90% in the TM corridors. By 2015, the complete TM system is expected to transport 80% of the city's population at an average speed of 25 km/h, with a service quality similar to an underground metro system (Echeverry et al, 2005).

Grutter Consulting (2006) have conducted an *ex ante* analysis of the expected annual CO₂ emission impacts of Phase II of TM as part of the application for CDM approval, taking account of car traffic reductions, fleet substitution and altered load factors. Phase II is expected to save on average around 250 000 tCO₂ per year from 2006 to 2012, equivalent to more than 50% of the nearly 400 000 tCO₂ in their Baseline scenario for affected corridors and adjacent areas of the city.⁷ CO₂ reduction levels rise annually as the system comes on line and longer-term effects occur. Over 20 years, the total saving could exceed 6 million tonnes of CO₂ equivalent. With a total project cost of about USD 530 million (about USD 12 million per km), the average CO₂ reduction cost over 20 years would be of the order of USD 90/t CO₂ eq. This assumes all other benefits are equal to operating costs of the system. If there are net benefits, which is likely, it would reduce the societal cost per tonne for the CO₂ reduction.

7. The net reduction from TransMilenio Phase II as percentage of all transport emissions within Bogota was not reported but would obviously be much smaller.

INE (2008) assessed the impacts of the Insurgentes BRT corridor in Mexico City. Opened in 2005, it runs for 20 km as a single BRT line. The construction costs of about USD 32 million are much lower than for Bogota, at about USD 1.6 million per kilometre. Taking into account other benefits, such as time savings and pollution emissions reductions, INE estimates a positive net present value for the system, in contrast to the net cost estimated by Echeverry *et al.* (2005) for the Bogota system. INE estimates a societal net benefit equivalent to USD 44 for every tonne of CO₂ saved by the system.

Box 5.8 ► BRT and the Clean Development Mechanism (CDM)

Annex B countries of the Kyoto Protocol are allowed through the CDM to get credit for financing projects to reduce CO₂ emissions in developing countries as an alternative to more expensive emission reductions in their own countries. Up to 2008, few transport projects have been approved, and only one related to developing BRT or passenger modal shifting. In 2006, the first successful project for Bogota's TransMilenio Phase II was approved, allowing CDM financing by Switzerland and the Netherlands. Several other BRT initiatives have started the implementation process in 2008/09. Table 5.15 below indicates applications and their known status.

Table 5.15 ► BRT systems linked with CDM schemes

Country	Cities	BRT launch year	CDM implementation date	Parties involved
Columbia	Bogota	2000	2006	Switzerland, The Netherlands
	Pereira	2006	2009 (in validation)	The Netherlands
	Cali	2009	2010	The Netherlands
	Medellin	2009	2010	
Ecuador	Quito	1995		
China	Chongqing	2009	2009 (in validation)	The Netherlands
	Hangzhou	2010		
	Xiamen	2010		
	Jinan	2010		
	Dalian	2010		
India	Delhi	2010		
	Mumbai	2010		

Source: GTZ, 2007; Grutter Consulting, 2009.

Many other BRT initiatives are underway around the world but little information is available on their costs or CO₂ impacts. Applications are being made for CDM projects in the cities of Pereira (Colombia) and Chongqing (China). Although no published analyses are yet available for these systems, preliminary estimates of impacts from surveys on modal shift have been made by Grutter Consulting (2009).

Based on available information, the characteristics of four BRT systems and their estimated impacts on travel and CO₂ are reported in Table 5.14. There is a fairly wide range in estimates for all variables, which deserves further investigation in order to better understand the difference. CO₂ reductions per km of BRT vary widely, with two cities achieving nearly 1 000 t/km per year and two cities achieving nearly 3 000 t/km per year. The two larger systems are estimated to have about three times the CO₂ impact per km of system length as the two smaller systems.

For comparison, the IEA has estimated the CO₂ emissions reductions that would be achieved just from a modal shift to BRT from cars and taxis, using average trip distances provided in the studies and assuming fuel savings of 8 L/100 km of avoided car or taxi travel. This is shown in the last two columns of Table 5.16. This analysis indicates that a modal shift from cars and taxis alone would save only about one-third of the total CO₂ estimated in the reported studies. Grutter (2009) indicates that the additional CO₂ reductions (beyond those from modal shift from cars and taxis) come from impacts such as:

- The use of larger buses than conventional public transit and a modal shift from smaller to larger buses.
- Higher rates of passenger use, possibly due to the more effective usage of bus management systems, especially in off-peak hours.
- Improved bus fuel efficiencies due to higher average speeds and less stop-and-go traffic on dedicated routes.

Table 5.16 ► Characteristics and CO₂ impact estimates for selected BRT systems

Reported data and estimates from studies							IEA estimates based on car-taxi vkm reduction in studies	
	BRT line distance (km)	% shift from car/taxi to BRT	Vehicle travel reduction (million km)	Million vkm saved per km BRT	CO ₂ reduction per km per year (t)	Total CO ₂ reduction per year (t)	Calculated CO ₂ savings (tonnes/yr)	As a proportion of reported CO ₂ savings
Bogota	84	9%	435.0	5.2	2 940	247 000	83 520	34%
Mexico City	20	6%	23.0	1.2	900	18 000	4 416	25%
Pereira	30	16%	54.5	1.8	900	27 000	10 464	39%
Chongqing	82	21%	495.3	6.0	3 171	260 000	95 098	38%

Sources: Bogota, Grutter 2006; Mexico, INE 2008; Pereira and Chongqing, Grutter unpublished data.

Table 5.17 presents, for the same systems, the costs of the BRT infrastructure (in some cases including bus costs) and annual operating costs. These are compared with the total GHG reductions per year from Table 5.16 to give estimates of the direct costs of each scheme per tonne of CO₂ equivalent reduced each year, reflecting all costs and reflecting only system construction costs. Ignoring the co-benefits to which these costs should be attributed, this suggests savings ranging

from USD 47/t CO₂ eq to USD 241/t of CO₂ eq saved if all costs are included, and from USD 17/t to USD 112/t if only construction costs are included.

There is substantial variation in the cost of CO₂ savings between systems. Chongqing, with both a low capital cost per km and a large system, shows the lowest estimated cost per tonne CO₂. Pereira and Mexico City both have somewhat higher construction costs per km and a relatively small system size, whereas Bogota has a much higher construction cost per km but also the largest system size.

Table 5.17 ► BRT system and CO₂ cost reduction estimates

	BRT capital costs (million USD)		Annual operational costs	Capital cost per km, no buses (million USD)	Annualised capital costs over 20 years (no buses, USD millions)	IEA-estimated cost per tonne CO ₂ reduction (USD)	
	Total	Of which, for buses				System capital cost only	All capital plus operating costs
Bogota	554	n/a	7.8	6.6	26.3	112	144
Mexico City	50	18	1.9	1.6	3.5	87	241
Pereira	72	12	2.8	2.0	5.2	111	237
Chongqing	90	n/a	7.6	1.1	10.6	17	47

Sources: Bogota, Grutter 2006; Mexico, INE 2008; Pereira and Chongqing, Grutter unpublished data.

BRT CO₂ reduction potential

IEA's *ETP 2008* made estimates of the potential CO₂ savings that might accrue from BRT systems in 2050. On the basis of the assumptions made, these estimates suggested that savings of the order of 500 Gt of CO₂ eq per year should be achievable from 500 large cities, *i.e.* about 1 million per city. If cities such as Bogota or Chongqing are the norm, saving around 3 000 t of CO₂ eq per km of system per year, the average system would need to be around 350 km to achieve the IEA estimate for 2050. If cities such as Pereira or Mexico City turn out to be the norm, assuming no improvements in performance from increased scale, the average system would need to be 1 000 km long for the IEA estimate to be achieved.

More research is needed on the full impacts of BRT systems and how their design (as well as measurement methodologies) might affect estimates. Impacts from complementary policies, such as land-use change and the provision of non-motorised transport infrastructure, also need to be better understood.

Improving non-motorised transport

Non-motorised transport, such as cycling, walking, and even rollerblading, is both extremely energy efficient (powered by food) and in most circumstances far healthier than other passenger transport options. Along with land-use planning, improving

the infrastructure and opportunities for using this mode can help to create cities and towns that are conducive to walking and cycling, and in the process significantly cut motorised vehicle travel and associated emissions.

Cycling

Cycling is the most energy efficient way for a single person to travel a relatively short distance, e.g. 0.5 km to 5 km. It is particularly well adapted for city centres, as they also are very compact, and typical cycling speeds of 10 km to 30 km/h are well aligned with average safe urban speeds. The recent uptake of on-street bicycle rental services in about 30 mostly European cities, such as the Paris Velib system, and their widespread adoption by local residents has achieved modal shifts toward cycling very quickly.

The provision of infrastructure such as cycling lanes, bicycle parking, specific traffic signals to give cyclists priority at intersections, and a range of safety and security enhancements, together with the on-going development of pro-cycling policies and culture, has also increased bicycle use. Copenhagen, Amsterdam and Vienna are most well known for their efforts in this respect, but hundreds of other cities have equal or greater cycling mode share. Cyclists in these cities use bicycles to commute, to go out for the evening and to travel to other towns for visits. In the Netherlands, the cycling infrastructure extends between towns in many parts of the country, and can sometimes be the fastest way to travel between towns.

Table 5.18 provides a comparison of government spending on developing and maintaining the cycling infrastructure with cycling mode shares. Investment takes time to come to fruition: increasing spending to Amsterdam's levels is unlikely to result in a city's bicycle mode share to jump from a low figure to 35% very quickly. But a modal share of perhaps 5% to 10% should be achievable in many cities after several years of significant spending on infrastructure of around USD 5 to USD 10 per capita.

Table 5.18 ► **Correlation between cycling infrastructure funding and cycling overall mode share**

	Annual funding (USD per resident)	Cycling mode share
United States	1.5	1%
Portland (city in Western US)	3.5	4%
Berlin	6.0	10%
Copenhagen	13.0	20%
Amsterdam	39.0	35%

Source: Rails-to-Trails, 2008.

Box 5.9 ► Cycling case study: Copenhagen

In Copenhagen, the local authorities have long pursued policies to make cycling a valid and popular alternative for everyday commuting. Bicycle lanes are prevalent, and governed by explicit standards and objectives in terms of cycle speeds, minimising injuries and other indicators. Explicit targets have recently been set out in the document Cycle Policies 2002-2012. Targets include:

- The modal share of commuters cycling to workplaces in Copenhagen to increase from 33% to 40%.
- Cyclist injuries and deaths per kilometre to decrease by 50% compared to 2000.
- The proportion of Copenhagen cyclists who state that they feel secure cycling in town to increase from 60% to 80%.
- Travelling speeds on trips of over 5 km to increase by 10%.
- No more than 5% of cycle track surfaces to be deemed to be unsatisfactory.

In 2006, a new target was adopted for 2015; that 50% of workplace commuters should travel by bicycle.

The annual cycle traffic in and around Copenhagen was around 420 million km in 2006, which represents about 350 km per inhabitant of Copenhagen urban area per year or 1 km per day. Local authorities invest EUR 6.7 million each year to improve cycling conditions and implement the programme set out above.

On-street bicycle rental services

In 2008, more than 40 000 bicycles were available from the rental services launched in over 30 cities around Europe. In Northern America, Washington, DC and Chicago are showing interest in similar schemes. A recent survey of cyclists in Paris (including Velib users) showed that Velib users took shorter cycle trips on average than those riding privately owned bicycles. Such outcomes can result from pricing policies, which discourage longer rentals.

In Paris, the first 30 minutes of rental are free of charge. At a speed of 10 km/h, 5 km can be covered in a half-hour rental, which allows trips nearly halfway across the city of Paris. The average Velib trip is less than 25 minutes, and only 12% of the surveyed trips exceeded 30 minutes, as compared with 20% of private bicycle trips. About 12% of Velib users travelled by private car before switching to bicycle rentals. Velib are seen to provide a viable alternative to cars, especially for short-duration trips.

Most on-street rental services are operated by urban advertisement (e.g. billboard) suppliers. Municipalities often provide these companies with extra advertisement locations, and the revenue generated by this helps to cover the costs of setting up, operating and maintaining the rental system, allowing low fees to be charged to users. This suggests that building and operating bicycle rental systems is unlikely to be profitable at acceptable price levels without additional subsidies.

Box 5.10 ► **On-street bicycle rental services around the world: Political fashion or alternative mode?**

As of early 2009, 31 on-street bicycle rental services had been or were in the process of being launched. Most are in Europe, with the largest number of schemes in France. It is unclear whether current growth rates will be sustained for very long, and whether such schemes will spread to other parts of the world. Table 5.19 lists cities with on-street bicycle rental programmes, with year of launch and the number of bicycles in the system. Paris's Velib system predominates with three times more bicycles than the next largest system in Barcelona.

Table 5.19 ► **On-street bicycle rental service around the world, 2009**

France			Rest of the World		
City	Year of launch	Number of bicycles	City	Year of launch	Number of bicycles
Aix-en-Provence	2007	200	Brussels	2006	250
Amiens	2008	313	Barcelona	2007	6 000
Besançon	2007	200	Córdoba	2004	35
Caen	2008	350	Dublin	2009	500
Cergy-Pontoise	2008		Gijón	2004	53
Dijon	2008	400	Gothenberg	2009	150
Lyon	2005	4 000	Luxembourg	2008	200
Marseille	2007	1 000	Milan	2008	1 400
Mulhouse	2007	200	Oslo	2006	1 200
Nantes	2008	700	San Francisco	2008	120
Paris	2007	20 600	Zaragoza	2008	400
Perpignan	2008	150	Sevilla	2007	2 500
Plaine-Commune	2009	450	Stockholm	2006	1 000
Rennes	1998	200	Vienna	2004	500
Rouen	2007	175	Washington DC	2008	150
Toulouse	2007	1 470			

Note: In the Paris region there will be 25 000 bicycles available by the end of 2009 once the Velib system is extended to the cities immediately surrounding Paris.

Future scenarios, and costs and benefits for increased cycling

Cycling is best adapted to city centres and densely populated areas. By 2050, 1.5 billion people are expected to live in cities with 1 million or more inhabitants. If a 5% increase in mode share for cycling could be achieved in these cities, and an

equal impact were achieved in towns and villages containing another 1.5 billion people, car travel would be cut by around 600 billion km per year worldwide, saving 100 million t of CO₂ eq emissions.

If it cost an investment of USD 5 per person per year to achieve this 5% mode shift, as in Table 5.20, the total investment required would be of the order of USD 15 billion per year. But this would be more than offset by the direct cost savings for fuel alone which, at USD 60/bbl, would be around USD 25 billion per year. With other benefits including a healthier population, reductions in traffic congestion and emissions, and time savings, the total cost of the cycling infrastructure would probably be very small compared to the net benefits, and the CO₂ savings would come at negative cost.

Table 5.20 ► Potential cycling increase and impacts by 2050

Population covered (billions)	Cycling modal share increase	Reduction in vehicle km per capita per year	Fuel savings (billion litres)	CO ₂ reduction per year (million t CO ₂ eq)
3	5%	200	40	100

Walking

Walking still is the widest used mode of transport in terms of trip share. But its share of distance travelled has declined very significantly during the last century as other faster modes of travel have grown. In most countries it is still the most used mode for trips shorter than 3 km. Motorised modes of travel have encouraged sprawl, making it less interesting and less practical to walk in many developed areas.

Walking can be increased by such measures as:

- Providing walker-friendly basic infrastructure such as side walks.
- Having well-marked and respected cross walks on city streets.
- Traffic calming measures such as speed bumps.
- Creating car-free zones.
- Improving personal security.
- Better law enforcement.
- Information campaigns.

Around the world, especially in parts of the developing world, pedestrian infrastructure, amenities and services are often neglected and under-prioritised in municipal and national budgets. Pedestrians in developing countries are especially at risk of injury or death. Helping city planners to understand and improve local pedestrian conditions is an important step in improving levels of walking.

Box 5.11 ► **Walking to school: a virtuous circle**

Many cities have implemented programmes to encourage people back to walking to school, as shown in Table 5.21. This has declined in recent years in response to a vicious circle: parents begin to feel that the trip to school for their children is becoming unsafe and unsecure; they start driving them to school, increasing vehicle traffic near schools; this leads to further safety concerns, which leads to more driving to school.

In these walking programmes, most of the households live close to school, so shifting back to walking is not too difficult. Support can come in the form of increased numbers of crossing guards, parents that volunteer to monitor certain streets, and advertisement campaigns to promote walking.

These programmes may also help to shape the attitudes of families and particularly the children themselves regarding their future mobility.

Table 5.21 ► **Walk to school schemes in place in Europe**

City	Country	Scheme
Alzira	Spain	Implementation by school
	Austria	National campaign
Stockholm	Sweden	Full tool kits for parents and schools
Orebro	Sweden	Implementation by parents
Linköping	Sweden	Implementation by school
Lyon	France	Tool kit for schools
Southend	United Kingdom	Incentives for schools and children
Camden - London	United Kingdom	Incentives for schools and children
Richmond - London	United Kingdom	Safe zone around school
Rome	Italy	City-wide campaign
	Lichtenstein	National campaign
Lausanne	Switzerland	City-wide campaign
	Canada	Incentives for parents and children
	Belgium	Game for children
Odense	Denmark	Game for children

Source: ELTIS database.

As a first step towards helping cities to improve their pedestrian infrastructure, Krambeck (2006) has worked with the World Bank to develop a measure called the Walkability Index. The index is based on 22 different measures that are scored through institutional and personal surveys. These include, for example, ten physical characteristics for a walking pathway:

1. Modal conflict, *i.e.* the presence of other modes such as bicycles or motorcycles.
2. Security from crime.
3. Crossing safety.
4. Motorist behaviour.
5. Amenities such as benches and street lighting.
6. Disability infrastructure and sidewalk width.
7. Maintenance and cleanliness.
8. Obstructions, such as from hawkers.
9. Availability of street crossings.
10. Volume of use.

The Walkability Index has the merit of being relatively simple to understand and to use, offering policy makers and planners a means of assessing and improving the walker-friendliness of pedestrian pathways. It would benefit from refinement. But the possibility of quantitatively scoring various aspects of walkability and identifying needed improvements, including the ability to compare cities, offers an attractive prospect worthy of further attention.

Future scenarios for walking

As for cycling, it is possible to develop future scenarios for walking based on modal shifts. But in most parts of the world, walking already constitutes a very high share of trips. On average 50% or more trips are made on foot in many cities, towns and villages in most of the developing world. All trips in all parts of the world begin and end with a walking component. So the goal for walking is not only to increase opportunities to walk but also to preserve those that already exist. In theory, if cities and towns can be made more pedestrian friendly and made dense enough to make walking an attractive option, car travel and even car ownership rates might be far lower in 2050 than they would be otherwise.

Walking is best considered in the context of a comprehensive strategy to make cities easier and more attractive to live in, and as an integral part of moving from a private vehicle-dominated system to one featuring more mass transit and non-motorised travel.

Developing packages of measures

Although it has been possible to make various estimates of the potential impacts of different measures for promoting modal shift, estimating the potential impact of combinations of measures is difficult and likely to be very case-specific. But given a long enough time frame and a well-enough designed set of policies, a fairly large impact on travel levels and mode shares appears possible. In the examples

discussed in this chapter, it has been shown that some cities have enabled cycling to reach 30% of all urban trips; that managing land use can reduce the number of trips elsewhere by up to 30%; that imaginative parking policies can achieve at least a 10% shift in mode share away from private vehicles; that BRT systems can shift at least 5% of trips from cars to mass transit; and so on. These effects cannot, obviously, simply be added together. To plan and manage policies to best effect, accounting for synergies and avoiding double counting, would require detailed travel models, almost certainly best developed for a specific city or region.

But it is possible to consider packages of measures that broadly taken together are likely to achieve a particular outcome, as in the BLUE Shifts scenario where LDV use is cut by 25% by 2050. Two such packages are shown in Table 5.22, recognising the different problems and opportunities that present in OECD and non-OECD countries. This indicative picture suggests that with a small contribution from each of a number of different elements, a 20% cut in travel compared to the Baseline figure should not be beyond reach. These measures are not explicitly linked to the BLUE Shifts scenario, but suggest one among many ways in which an important element of that scenario might be achieved.

Table 5.22 ► **Simplified, indicative packages of modal shift policies and potential impacts on LDV travel**

	OECD	Non-OECD
Urban planning and land-use changes	10%	10%
Investments in transit systems and non-motorised transport infrastructure	5%	10%
Parking policies and road pricing	5%	2.5%
ITS, telematics and other supporting policies	5%	2.5%
Total	25%	25%

Much greater reductions in LDV travel may be possible and may be cost effective in their own right and/or relative to other transport policy objectives. More work is needed to better understand the full potential, costs, and benefits of different packages, and to better develop an optimal set of targets for specific countries and cities. This chapter has made what can only be considered a first approximation of some of the CO₂, cost and other impacts that could result from various travel policies as a basis for debate and further work.

Chapter 6 TRUCK AND RAIL FREIGHT TRANSPORT

Key findings

- ▶ Truck and rail transport together accounted for about 600 Mtoe, or 27% of global transport energy use in 2006. About 90% of that energy was used by trucks. In the Baseline scenario, trucking energy use by 2050 is projected to increase by 50%, with the quantity of freight moved by trucking¹ worldwide expected to nearly double, and energy efficiency to improve by 20%. Rail freight volume is expected to increase by around 50% with a similar 20% improvement in rail efficiency. The vast majority of this growth will occur in non-OECD countries, although freight transport per capita will remain below OECD levels.
- ▶ Average trucking efficiency has steadily improved in recent years although the performance of trucks varies considerably in different countries and even across similar truck classes in the same country. These variations suggest that considerable fuel savings could be achieved if all fleets were to achieve the fuel efficiency of the best fleets. While in the IEA Baseline scenario trucking efficiency improves by about 20% by 2050, in the BLUE Map scenario it reaches 33% as a result of additional technical and operational improvements. Improving trucking logistics may play an important part in this, but relationships are complex and the potential energy savings are uncertain.
- ▶ Most freight, whether it is moved by truck or by rail, relies on oil, in particular diesel fuel. To cut CO₂ emissions, rail may have good opportunities to shift to much greater use of electricity, through the electrification of lines. The main opportunity for trucks to cut CO₂ emissions via alternative fuels is likely to lie in the use of advanced biofuels, subject to availability.
- ▶ Apart from a few large countries that move raw materials long distances, such as Russia, the United States and China, rail accounts for a relatively small share of freight movement compared to trucks in most countries. The efficiency of rail freight can be improved, but it is already so much more efficient than road freight that its biggest potential contribution to CO₂ emissions reductions would result from modal shift from road to rail, where possible. It is worth redoubling efforts around the world to foster such a modal shift.
- ▶ Increasing rail freight's share of the total volume of freight movement will require major investments both in rail infrastructure and in intermodal facilities to allow goods to be easily moved on and off rail systems. This would need to be stimulated by strong government intervention such as support for much greater investment in such facilities.

1. Measured throughout this chapter in tonne-kilometres (tkm).

- ▶ *An IEA BLUE Shifts scenario for freight, in which half of all the future Baseline scenario growth in heavy, long-haul trucking is shifted to rail, results in an increase of 20% in the volume of rail freight movements globally in 2050. This would require a very significant transformation in the way in which freight is transported. The net impact would be a reduction of about 15% in combined truck/rail energy use and CO₂ emissions compared to the Baseline scenario.*
- ▶ *Many of the options for improving fuel efficiency in and reducing CO₂ emissions from truck and rail freight appear to be relatively low cost. This includes truck efficiency retrofit packages, driver training, better logistic systems, and (in some countries) lower speed limits. But much more work is needed to better estimate the costs and benefits of different technologies, logistics systems and other options.*

Current situation and recent trends

Data on surface freight movement in many countries is poor, but most freight moved by road and rail appears to be moved within rather than between countries. In the European Union, for example, available data for 2005 indicates that only around 30% of all road freight (in terms of tonne kilometres - tkm) crossed an international border (Eurostat, 2007). The corresponding figure for rail freight, which accounted for 19% of all surface freight in the same year, was 51%.

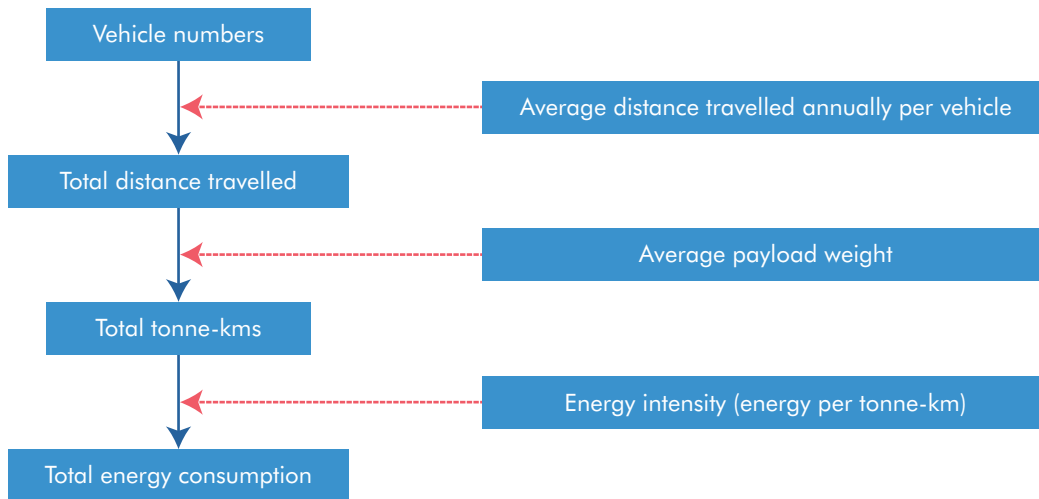
Most intercontinental freight is carried by shipping. Of the three main intercontinental trade routes, Asia-North America, North America-Europe and Asia-Europe, only the Asia-Europe route offers the potential for surface transport links. Very little freight traffic currently moves on this route by rail or road. In 2005, for example, less than 5% of full load containers moving between China and Europe moved by land-based modes (Farahmand-Razavi, 2008).

The factors affecting the energy consumed by freight transport can be broken down into a series of steps, as shown in Figure 6.1.² Tracking these different steps and understanding how changes in each over time affect energy use and CO₂ emissions can help in the development of policies to achieve specific policy objectives.

GDP is a major driver of the demand for goods and, therefore, of the movement of goods and has an important influence on all of the variables in Figure 6.1. It is particularly important to understand the relationship between GDP growth and variables such as total movement overall and by mode, average payload weights and fuel efficiency. But data to underpin such analyses are unavailable for most non-OECD countries. The IEA has made estimates where possible.

In 2005, trucks used a total of about 500 Mtoe (21 EJ) of energy worldwide, about 23% of the total energy consumed by the transport sector in that year (IEA MoMo estimates). Rail freight used about 40 Mtoe (2 EJ), i.e. less than 10% of that used by trucks.

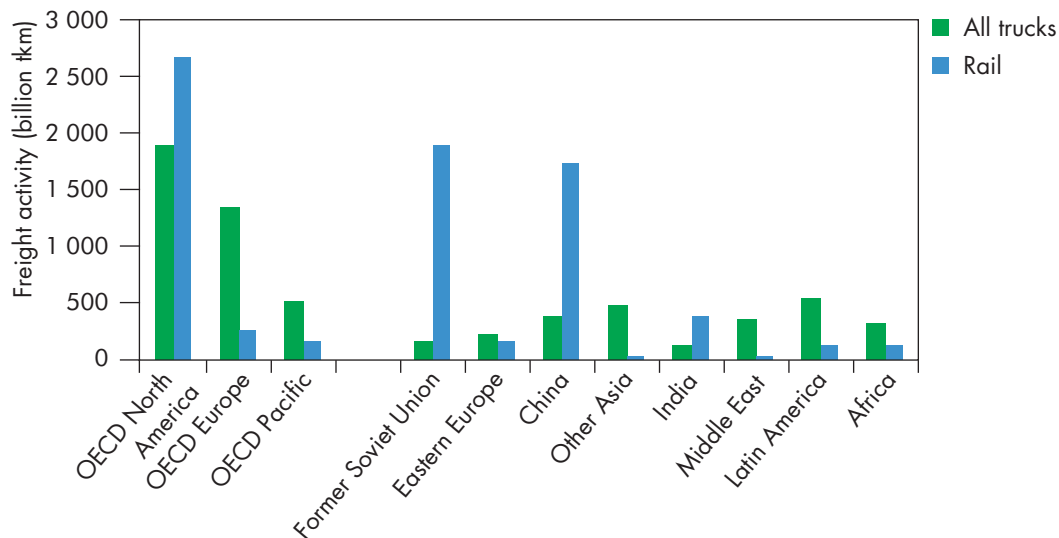
2. Developed by A. McKinnon as a basis for sectoral analysis. Dr. McKinnon provided much of the analysis underpinning this chapter.

Figure 6.1 Relationships and variables affecting freight transport energy use**Key point**

Total energy consumption per tonne km depends on the number of vehicles, the average distance they travel, and the extent to which they are loaded.

These data reflect both trucking's high share of freight movement in most regions and rail's much better average efficiency. MoMo estimates of rail and trucking shares by region in 2005 are shown in Figure 6.2. Rail tonnage outstrips truck tonnage mainly in physically large countries and in regions that move large amounts of raw materials such as the United States, Russia, China and Australia.

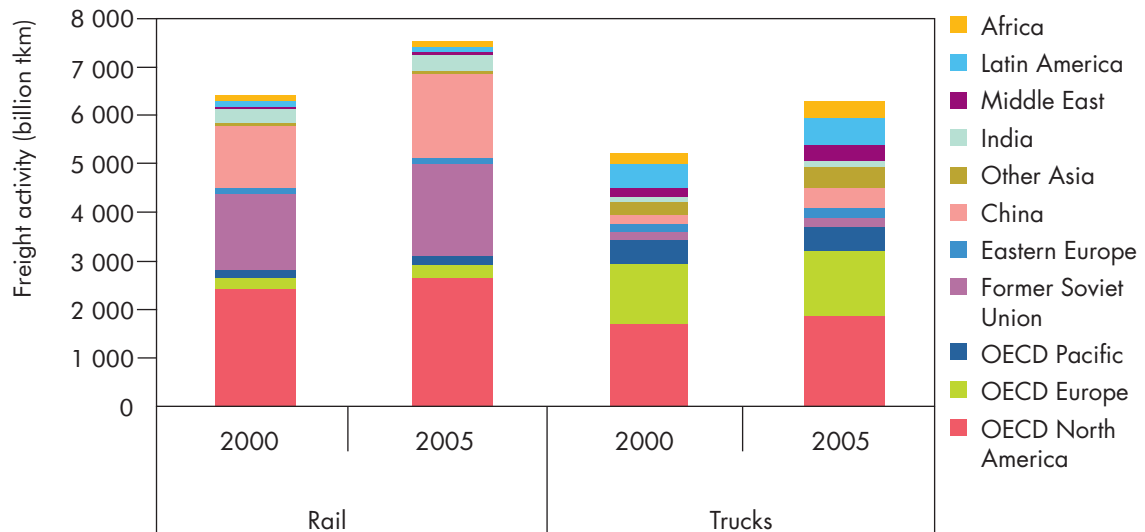
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Figure 6.2 Freight transport by truck and rail, 2005**Key point**

The modal choice is not homogeneous across world regions. Rail out-strips truck in large countries and in regions rich in raw materials.

Figure 6.3 shows the recent freight trends for road and rail by region, based on available data and IEA estimates. In most regions, the total amount of freight moved by both modes has been increasing, though the rates of increase vary widely between countries. Even within Europe, growth rates vary considerably. For example, road tonnage rose by 93% in Spain and fell by 7% in the Netherlands between 1999 and 2007. Worldwide, total rail volumes are higher than total road volumes, but they are concentrated in a small number of countries, and growing more slowly than road freight.

Figure 6.3 ► Road freight trends by region, 2000 and 2005

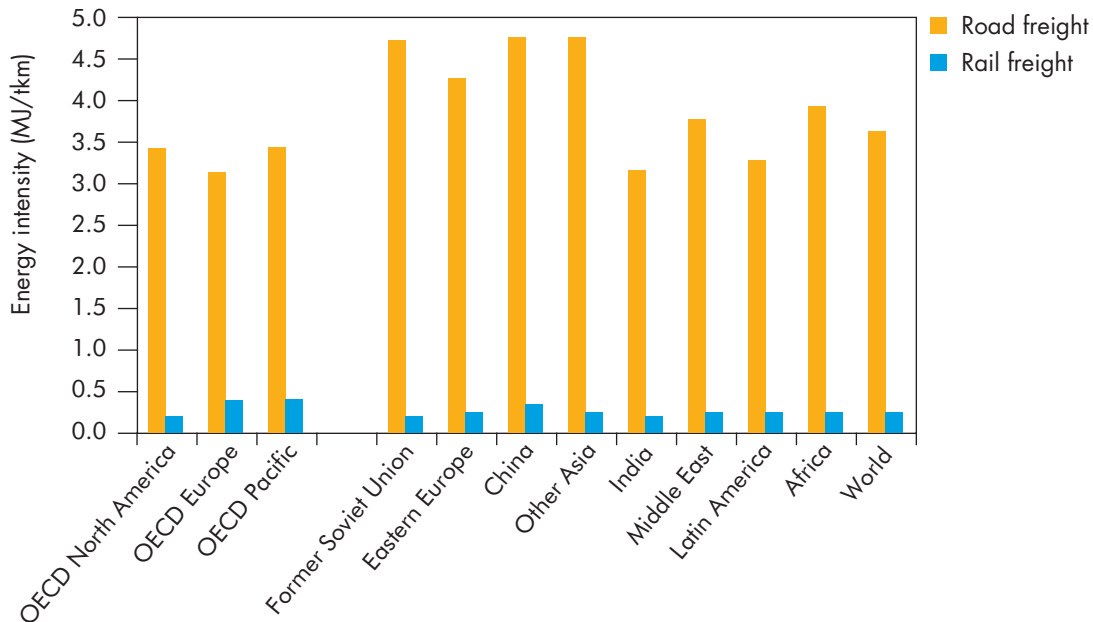


Key point

Freight trends for road and rail by region reveal that total rail volumes are higher than total road volumes, but rail volumes are concentrated in a small number of countries.

Despite moving more freight, rail uses far less energy than trucking because of its much higher average efficiency. Relative energy intensities are shown by region in Figure 6.4. The difference ranges significantly between regions, depending mainly on the types of goods moved. For example, in the Former Soviet Union large quantities of bulk raw materials are moved very long distances by rail at very low average energy intensities, whereas in OECD Europe much more rail freight comprises the transport of lighter, finished products.

The difference in energy efficiencies has consequences both for the fuel used and for the CO₂ emissions per tkm of freight moved. In regions where rail is electrified and electricity generation emits few GHGs, such as in the European Union, rail can offer very significant CO₂ benefits over trucking. All regions could achieve large CO₂ savings through a combined strategy to shift freight from road to rail, electrify their railways and decarbonise their power generation.

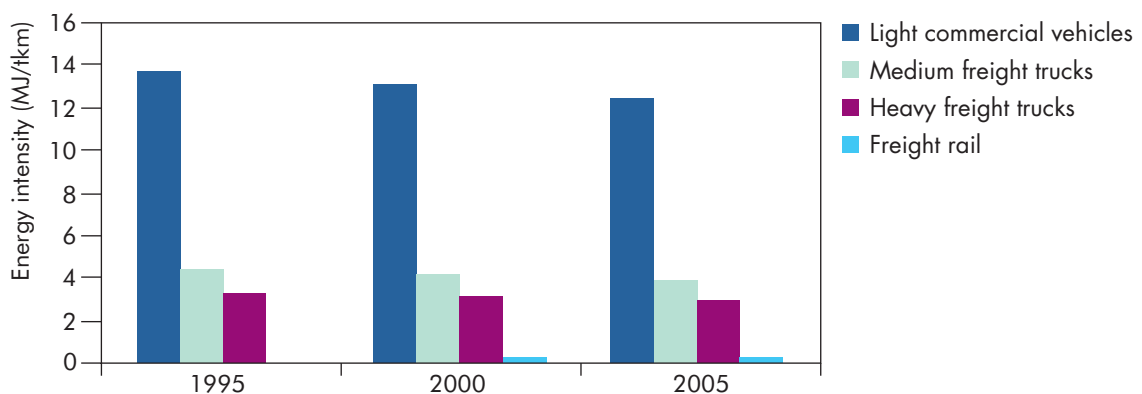
Figure 6.4 ▶ Energy intensity, truck and rail, by region, 2005

Source: IEA MoMo data and estimates.

Key point

Energy intensity (expressed in units of energy required per tkm) of rail freight transport is just a fraction of the energy intensity for road freight.

Figure 6.5 shows the average energy used per tkm for different truck types and for rail transport over time. This shows a wide range of levels of energy efficiency for different size trucks, and slow but steady improvements in trucking energy efficiency.

Figure 6.5 ▶ Global average energy intensity trends by surface freight category

Note: no data for rail is available before 2000.

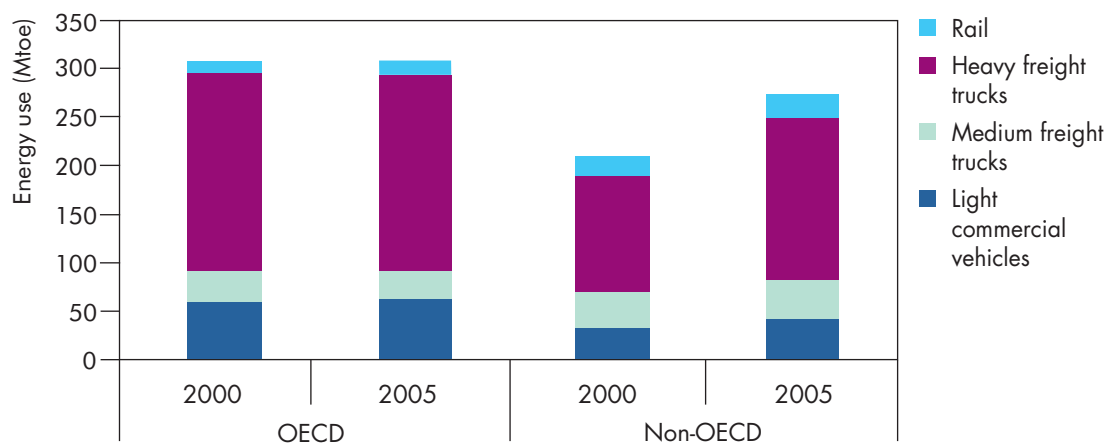
Source: IEA MoMo data and estimates.

Key point

Average energy intensities are significantly affected by the carrying capacity of the mode and the vehicle chosen.

Total energy use by trucks and rail in 2000 and 2005 in OECD and non-OECD countries is shown in Figure 6.6. Trucks, particularly heavy trucks, dominate energy use in both regions. Energy use is growing much faster in non-OECD countries than in OECD countries. Given the trend, non-OECD countries' truck/rail freight energy consumption is likely to exceed OECD countries' consumption for the first time in around 2010. Rail energy use is already higher in non-OECD countries, primarily on the extensive rail systems in Russia and countries of the Former Soviet Union, than in the OECD.

Figure 6.6 ► Energy use by freight category, OECD and Non-OECD, 2000 and 2005



Key point

Energy use in OECD and non-OECD countries is mainly associated to road freight modes.

Truck and rail freight transport: future scenarios

The analysis in this chapter helps to develop the truck and rail freight scenarios included in the Baseline, High Baseline, BLUE Map and BLUE Shifts scenarios. BLUE Map includes strong uptake of efficiency measures and alternative fuels for truck and rail. BLUE Shifts involves a significant shift of freight transport from truck to rail. The impacts of the different scenarios on freight movement by types of truck and rail are shown in Figure 6.7.

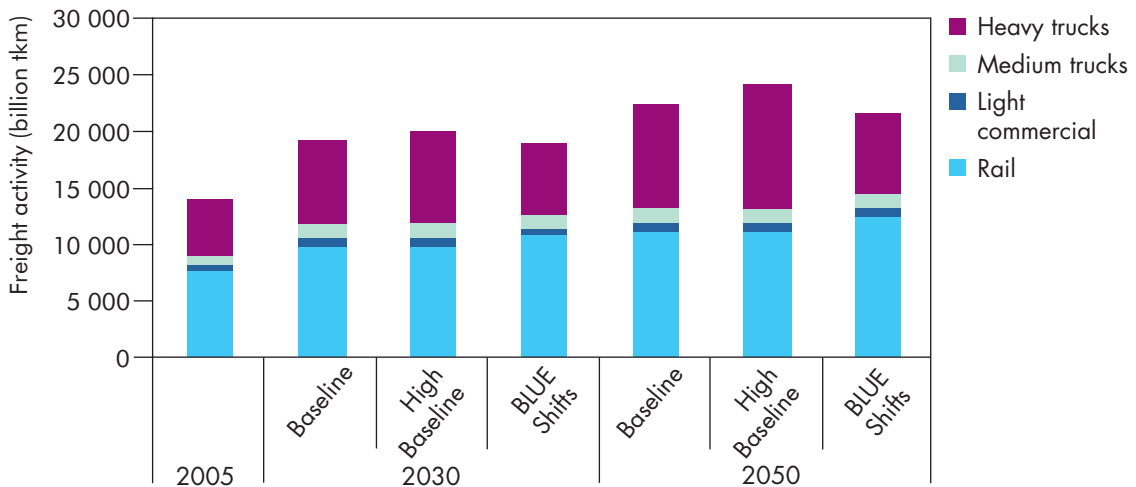
The growth in the Baseline scenario reflects assumptions about the rate of growth in trucking and rail freight movement that is consistent with projected increases in population and incomes, and with historical relationships. In the Baseline scenario, a considerable amount of decoupling occurs between income growth and freight transport, consistent with expectations that much of the growth in future GDP will be in sectors other than manufacturing. The High Baseline scenario provides an alternative view, with less decoupling. This results in levels of truck transport in 2050 about 20% higher than in the Baseline scenario. If this scenario comes to fruition,

it will be more difficult to decarbonise freight transport than if the Baseline scenario prevails.

The BLUE Shifts scenario shows about the same overall level of freight transport in 2050 as in the Baseline scenario, but with a significantly greater share by rail transport and proportionately less by truck transport. The BLUE Shifts scenario assumes that half of the growth in heavy truck transport in the Baseline scenario can be shifted to rail, resulting in a 35% increase in heavy truck tkms between 2005 and 2050, rather than the 75% increase in the Baseline scenario.

These assumptions help to show the energy and CO₂ reductions that could be achieved if policies capable of delivering such a scenario were to be put in place. Approaches and costs for achieving such outcomes are discussed in the following sections of this chapter. But more work is needed to better understand the potential for rail systems in different countries to expand and accommodate further growth in freight transport. The ability to use intermodal systems to shift transport from truck to rail also needs more research and development, especially for non-OECD countries.

Figure 6.7 ► Global truck and rail transport projections by mode, scenario and year



Key point

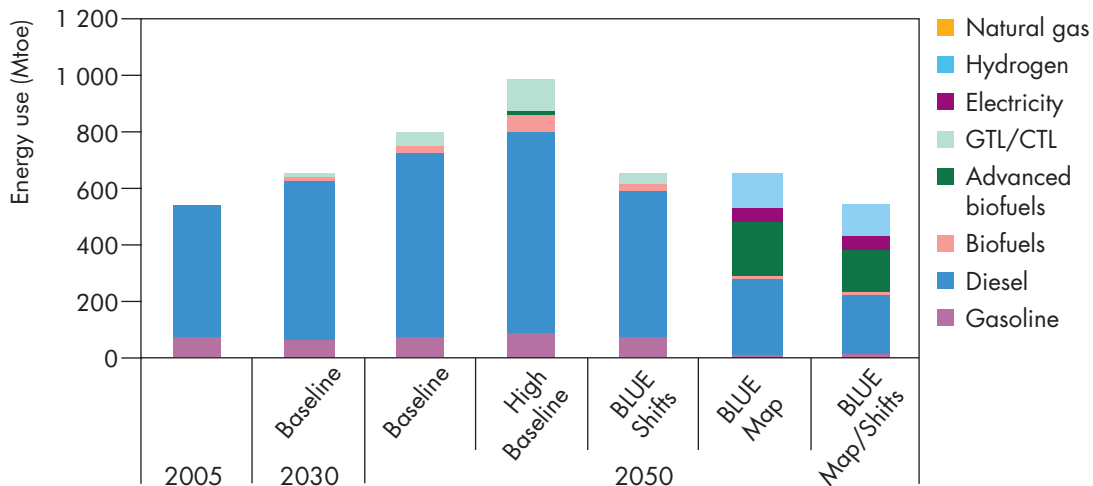
The BLUE Shifts scenario involves a significant shift of freight transport from truck to rail.

Figures 6.8 and 6.9 show the impact of the different scenarios on fuel use for trucks and rail, respectively. In the Baseline and High Baseline scenarios, trucking energy use increases by about 50% and nearly 100%, respectively. The 20% increase in rail energy use in the Baseline scenario is unchanged in the High Baseline scenario, reflecting the assumption that all the additional growth between the Baseline and High Baseline scenarios is assumed to be carried by road. The use of CTL and GTL fuels in trucks is assumed to become significant after 2030 in the High Baseline scenario, as it does in LDVs and aircraft, reflecting the increasing production of new types of hydrocarbon fuel to meet demands that exceed the then available production of conventional petroleum sources.

The BLUE Shifts and the BLUE Map scenarios are shown separately and also combined. For trucks, both the BLUE Shifts and BLUE Map scenarios result in about a 20% reduction in fuel use in 2050 compared to the Baseline scenario. This increases to almost a 40% reduction when the two BLUE scenarios are combined although the result is slightly less than the sum of the two individual cases, since as trucks improve their efficiency, the benefits of shifting to rail are reduced. The outcomes envisaged in the BLUE Map scenario are achieved by a strong movement away from petroleum fuels, in particular to advanced biofuels. This is due to the uptake of second-generation biofuels as a blend in diesel fuel reaching 30% by 2050. A certain number of hydrogen fuel cell trucks, plug-in hybrid trucks and pure electric trucks are also assumed in this scenario, mostly for light commercial and medium-duty freight movement.

The additional energy reductions achieved by combining the BLUE Map and BLUE Shifts scenarios come from the shift from road to rail freight assumed in the latter scenario. As shown in Figure 6.9, as a result of this shift, rail freight uses more energy in the BLUE Shifts scenario than in the Baseline scenario. But when this scenario is combined with the assumptions underlying the BLUE Map scenario, including about a 25% improvement in rail efficiency led by a strong shift towards more efficient rail electrification, rail energy use in 2050 is brought back down to the level of the Baseline scenario.

Figure 6.8 ▶ Truck energy use by fuel, scenario and year

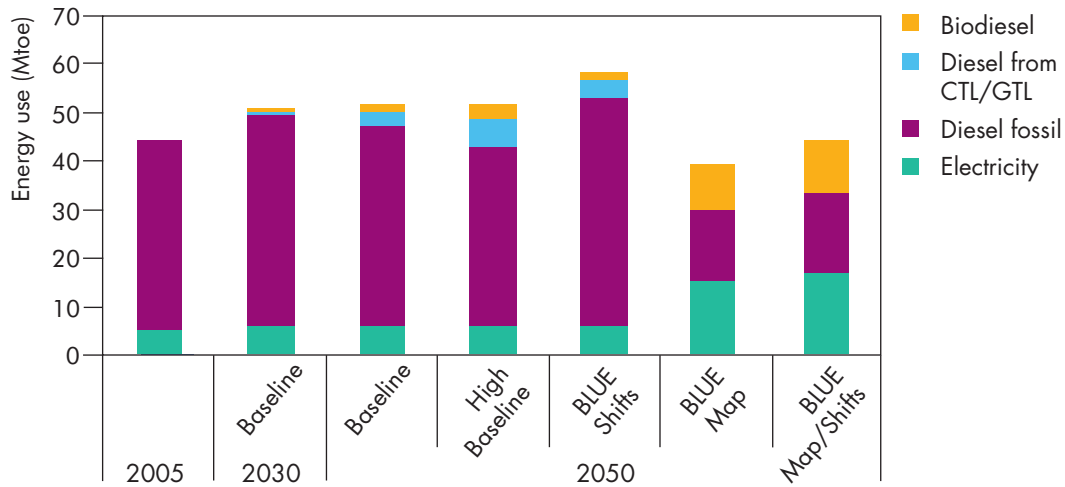


Key point

Fuel use for trucks changes in different scenarios, influenced by efficiency, vehicle technologies, increased fuel switching and modal shift.

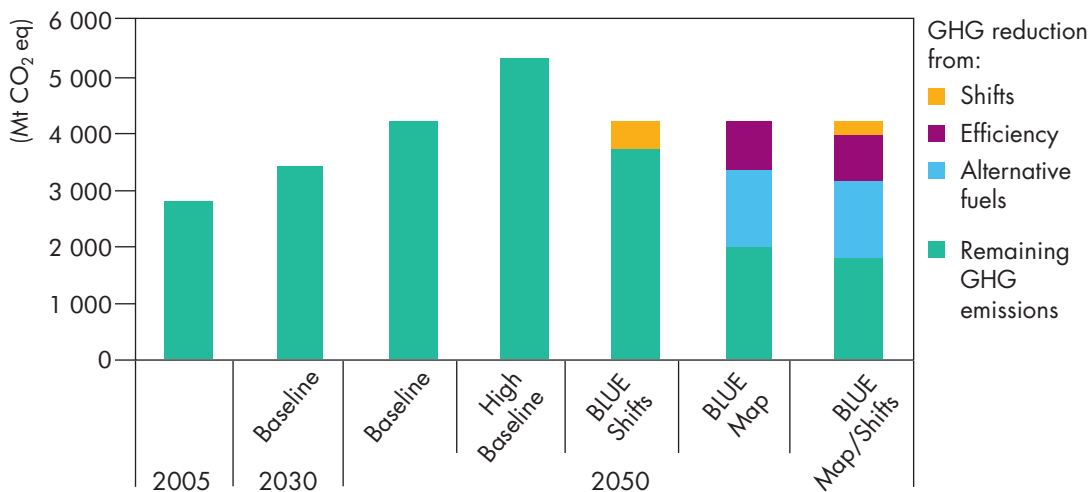
The impacts on GHG emissions³ of modal shifts, fuel efficiency improvements and shifts to alternative fuels are shown in Figure 6.10. Compared to the Baseline scenario in 2050, the shifting of freight transport from heavy truck to rail in the BLUE Shifts scenario reduces total surface freight CO₂ equivalent GHG emissions by about 15%. Efficiency improvements, additional to those already in the

3. CO₂ equivalent, well-to-wheels.

Figure 6.9 ▶ Rail freight energy use by fuel, scenario and year**Key point**

Fuel use for rail is affected by the changes different scenarios, especially through increased fuel switching and modal shift.

Baseline, reduce emissions by a further 15%. Shifts to alternative fuels, especially advanced biofuels for trucking and electricity for rail, achieve a further reduction of about 25%. Taken together, the three changes yield almost a 50% reduction in GHG emissions from surface freight in 2050, and about a 10% reduction compared to 2005 levels. Additional emissions reductions are probably possible but they would depend on even more modal shifting, additional efficiency gains or fuel substitution. Potential approaches for achieving these outcomes are described in the following sections.

Figure 6.10 ▶ Well-to-Wheel GHG emissions and source of reductions from truck and rail freight by scenario**Key point**

GHG emissions from truck and rail freight is reduced thanks to increased efficiency, advanced vehicle technologies, increased fuel switching and modal shift.

Factors affecting truck and rail freight movement

The level and nature of the future demand for surface freight transport will depend on underlying trends in the key steps in the freight chain identified in Figure 6.1. These are affected by many different factors, some related to the external economic and political environment, others under the control of individual businesses.

These factors include:⁴

Economic growth: Economic development tends to increase the movement of freight, particularly by surface modes.

Restructuring of logistics systems: In recent decades, production and distribution systems have undergone a series of major structural changes, mainly involving the geographical concentration of capacity and activity.

Realignment of supply chains: Over the past 30 years, in many industrial sectors, operations have become increasingly vertically disintegrated. Extra links have been added to supply chains. The wider sourcing and marketing of products has also extended supply links, increasing the distance that freight moves.

Rescheduling of product flows: Under pressure to cut inventory and reduce order lead times, companies have adopted just-in-time supply systems, resulting in more frequent shipments of smaller quantities.

Changes in the management of transport resources: Decisions made at management level affect the choice of mode, vehicle size/type and the efficiency with which freight vehicles are operated.

As shown in Table 6.1, it is difficult to predict the overall impact of these factors on freight demand and energy use because they act in so many different and offsetting ways.

Table 6.1 ► An assessment of the impact of a range of economic factors on freight transport and energy use

	Key ratios						
	Tonnes	Modal split (road share)	Handling factor	Average length of haul	Average payload weight/size	Empty running	Energy intensity
1 Economic development trends							
Increased material consumption	↑	↑			↑		↑
Manufacturing growth	↑	↑	↑	↑	↓	↑	↑
Population growth	↑				↑		↑
Urbanisation		↑	↑	↓			
Improvements in transport infrastructure		↑	↑	↑			↑

4. This framework is adapted from the EU REDEFINE project (NEI, 1999).

Table 6.1 ▶ An assessment of the impact of a range of economic factors on freight transport and energy use (continued)

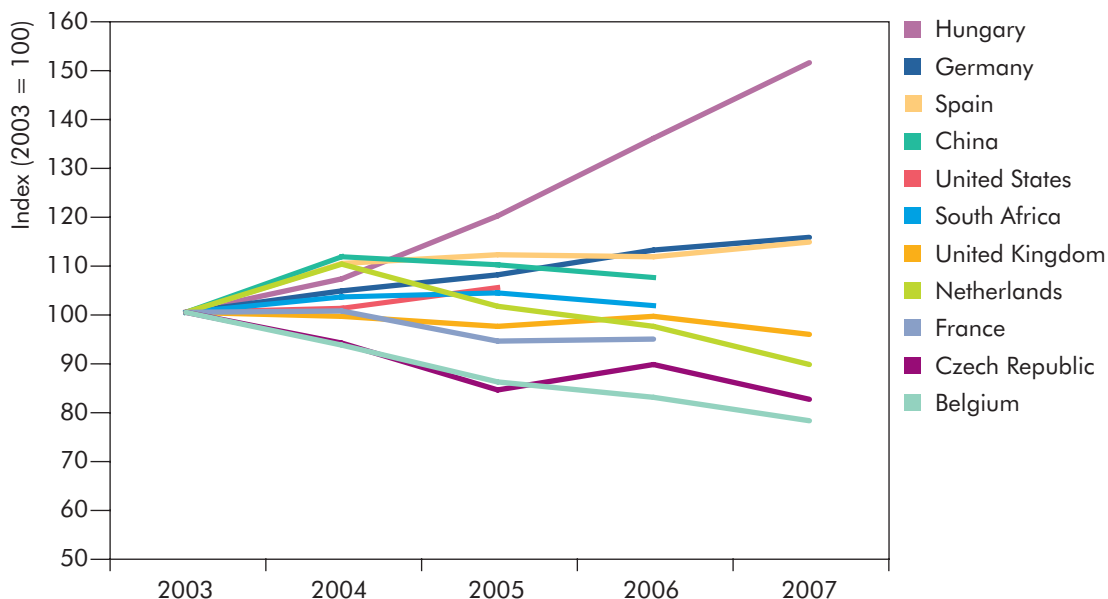
	Key ratios						
	Tonnes	Modal split (road share)	Handling factor	Average length of haul	Average payload weight/size	Empty running	Energy intensity
Transport deregulation		↑		↑	↑	↓	↓
Regional polarisation				↓		↑	↑
Increased traffic congestion		↓		↓	↓	↑	↑
Off-shoring of manufacturing	↓	↑	↓		↓		↓
Tightening environmental controls		↓			↑	↓	↓
2 Restructuring of logistics systems							
Spatial concentration of production		↑		↑	↑	↓	↑
Spatial concentration of inventory		↑		↑	↑	↓	↑
Development of break-bulk/transshipment systems		↑	↑	↓		↑	↓
Centralisation of sorting operation		↑	↑	↓	↑	↓	↓
Concentration of international trade on hub ports/airports			↑	↑	↑		↑
3 Realignment of supply chains							
Vertical integration of production			↓		↑		↓
Vertical disintegration of production		↑	↑	↓	↓	↑	↑
Wider geographical sourcing and distribution	↑	↓	↑	↑	↑	↓	↑
4 Rescheduling of product flows							
Just-in-time replenishment		↑	↑	↓	↓	↑	↑
Growth of 'nominated day' deliveries/delivery zone targeting					↑	↓	↓
Narrowing of delivery windows		↑			↓	↑	↑
5 Changes in management of transport resources							
Increased outsourcing of transport					↑	↓	↓
Switch traffic to rail		↓	↑	↑			↓
Increase in truck size/weight		↑		↑	↑	↓	↓
Adoption of fuel economy measures		↑					↓
Increased use of computerised routing and scheduling				↓	↑	↓	↓
Increase in loading matching services		↑			↑	↓	↓

Relationship between GDP and demand for freight transport

Historically, there has been a close correlation between GDP growth and freight growth. A World Bank study of 33 countries at different stages of development found that differences in GDP explained 89% of the variation in road freight volumes (Bennathan *et al.*, 1992). Much of the freight forecasting undertaken at national and regional levels has assumed that this relationship will remain very close, *i.e.* that the rate of change in tkms will continue to correlate closely with the rate of change in GDP. Recent analysis of freight transport intensity trends in a broad range of countries over the period 2003 to 2007 suggests this relationship may be more complex and variable than it appears. It is trending downwards in most large countries. But further work is needed to better understand these trends and what drives them (Figure 6.11).

The ratio of road and rail tkms to GDP has remained within a range of $\pm 20\%$ over the four years studied in most of the countries examined. Even within the European Union, some countries have seen a steep increase in surface freight transport intensity while others have seen a decline. In some countries, such as the United States and the United Kingdom, where freight was beginning to grow less rapidly than GDP, recent data suggests that the correlation between the two has strengthened again (McKinnon, 2007a). In China, the ratio of surface freight tkms to GDP declined slightly between 2003 and 2006.

Figure 6.11 ► Trends in the ratio of truck and rail volumes relative to GDP



Sources: IEA MoMo data, various sources including Eurostat.

Key point

Historically, there has been a close correlation between GDP growth and freight growth, but recent freight transport intensity trends in Europe suggest that this relationship may be more complex and variable than it appears.

There is some evidence to suggest that, beyond a certain level of development, freight volumes start to increase more slowly than GDP due to:

Shifts in GDP composition: The share of GDP associated with production industries declines and new economic growth comes increasingly from service and information activities, which generate less freight per unit value of output.

Shifts in value-to-weight ratios: As consumers' income increases and they trade up to more expensive, potentially less essential items, the weight of their purchases tends to decrease. Since 1990 in most OECD countries, GDP has risen faster than materials consumption.

Limits to distant sourcing: The centralisation of economic activity and wider sourcing of products, which have been responsible for much of the growth in freight in recent decades, cannot continue indefinitely. These factors will eventually peak, limiting any further growth in freight levels from this cause. This trend is at an advanced stage in most developed countries, although still at an earlier stage in many developing countries.

Off-shoring: In recent decades, industrial capacity has shifted very significantly from developed to developing countries, especially in the Far East and Eastern Europe, where labour costs are lower (Dicken, 2003). When domestic production is shifted to or displaced by production in another country, local consumption is replaced by imports. The upstream supply chain also moves off-shore, reducing the freight intensity of the off-shoring country and increasing it in the country taking over the displaced production.⁵

Overall, it is likely that continuing economic development over the next 40 years will see more countries entering the phase in which GDP grows faster than freight. This does not necessarily mean that the amount of freight movement will decline, merely that it will grow at a slower rate than the economy.

Other factors affecting freight transport growth

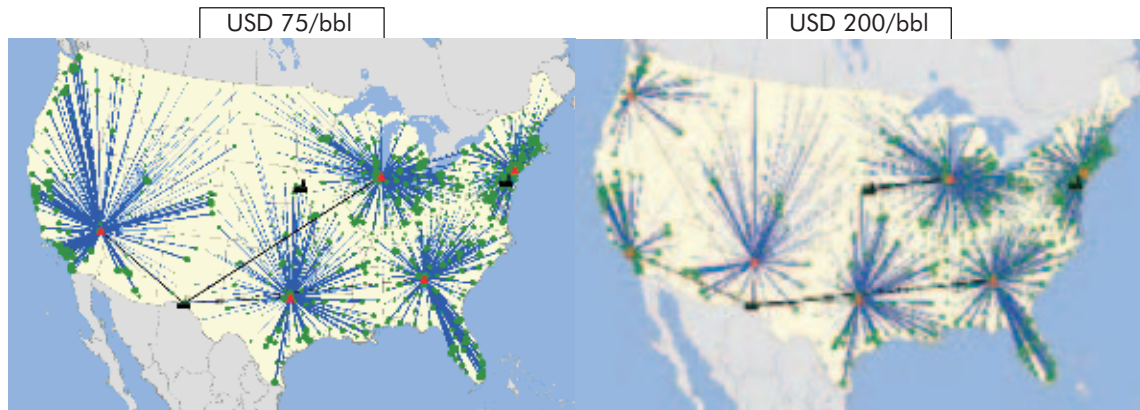
Future growth in demand for surface freight transport is also likely to be affected by other factors including rising energy and environmental costs. Rising oil prices and the imposition of environmental taxes or emission trading may increase the cost of transport and influence the cost trade-offs that companies make between transport, production, inventory and warehousing. But transport costs are often a small share of total costs and changes in them, unless they are substantial, may only weakly influence changes in production and transport activity.

A recent analysis by Accenture (Gosier *et al.*, 2008) has illustrated how, if oil prices rose from USD 75/bbl to USD 200/bbl, the resulting increase in transport costs would increase the optimal number of warehouses in one US manufacturer's distribution system from five to seven (Figure 6.12). This decentralisation would be likely to reduce freight volumes and related energy consumption. But against the

5. In practice, off-shoring is likely to result in a net increase in total freight energy consumption, partly because of its contribution to increasing international trade volumes and partly because the energy intensity of freight movement in developing countries is often significantly higher than in developed countries.

near-tripling of oil costs assumed, the change in the distribution system is perhaps surprisingly limited.

Figure 6.12 ► Change in the optimal structure of a distribution system with increasing oil price



Source: Grosier *et al.*, 2008; figure courtesy of David Simchi-Levi, MIT and Chief Scientist, ILOG, IBM Software Group.

Key point

Changes in oil prices can have fundamental consequences on the optimisation of logistics (e.g. in the number of warehouses in one US manufacturer's distribution system).

These findings reflect the fact that the average price elasticity of demand for freight transport is in general relatively low (Oum *et al.*, 1989). In modelling demand for road freight transport, price elasticity values of -0.1 to -0.2 are typically used, meaning that a 10% increase in transport costs induces a 1% to 2% reduction in demand. Sensitivity to oil price rises is even lower, as fuel prices represent on average 20% to 30% of total vehicle operating costs. In some countries, such as the United Kingdom, relatively high fuel duties further dampen the effect of changes in world oil prices on fuel prices (McKinnon, 2007b). The regulation of retail fuel prices in some developing countries, such as Malaysia and China, also weakens the signal from rising oil prices on surface freight demand. So increasing fuel costs, whether the increase comes from higher oil prices or from higher taxes or fees, appear unlikely to change significantly overall trends in freight movement, although they might encourage increases in freight transport efficiency.

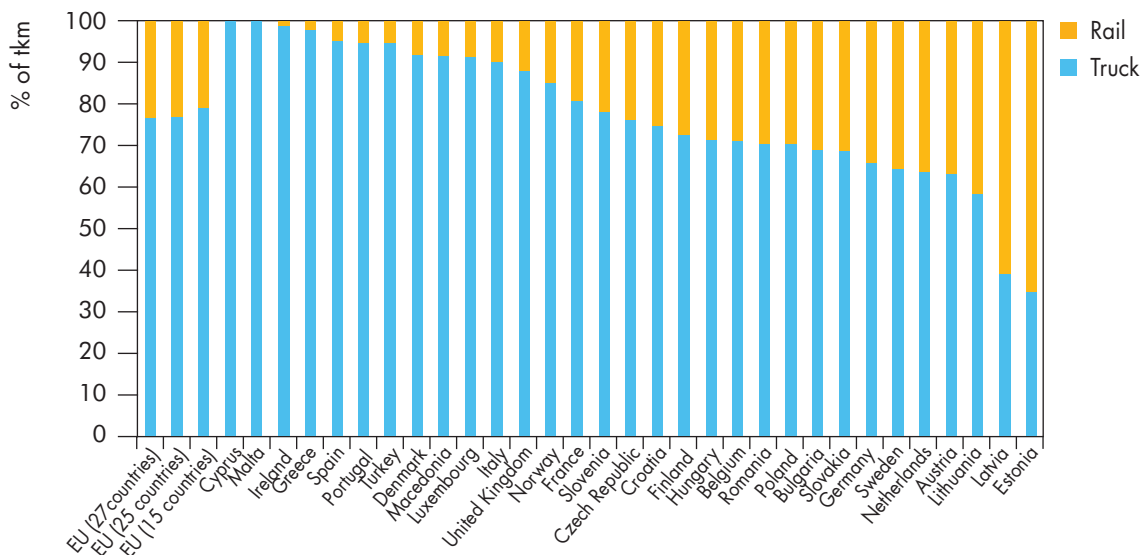
Traffic congestion may also have an impact on the rate of growth in freight volumes. In many parts of the world, traffic has been growing faster than the road infrastructure, increasing congestion not only on urban road networks, but also on inter-urban road corridors and rail networks, and at ports. Congestion does not appear to suppress freight demand. A recent study in the United Kingdom for the International Transport Forum (OECD) revealed that logistics managers can be very resourceful in working around congestion and adapting their operations to longer and less reliable transit times (McKinnon *et al.*, 2008). As a result, worsening congestion at ports, at rail terminals and on major overland corridors, may actually increase surface freight volumes by causing consignments to be routed more circuitously to avoid bottlenecks.

Taking these factors together, it is clear that efficiency improvements alone are unlikely to be sufficient to enable the freight sector to make a material contribution to net CO₂ emissions savings, given the expected 2% to 3% growth per year in freight volumes. If governments want freight transport to contribute to the achievement of their ambitious targets to cut CO₂ emissions by 50% to 80% by 2050, they will need to consider a range of policy options, including cap-and-trade systems with steadily reducing caps, taxes and possibly quota systems to reduce the volume of freight movement to acceptable levels.

Freight modal split

As rail transport is far more energy efficient than trucking, the more freight can be moved by rail, the greater will be the energy and CO₂ savings that will result. The proportion of surface freight transported by road and by rail varies widely between countries (Figure 6.13). Even within a single continent such as Europe, countries of similar sizes and levels of economic development can have markedly different road–rail splits. International variations in the modal split reflect differences in industrial structure, the geographical distribution of population and economic activity, the quality and capacity of the relevant infrastructure, and prevailing transport policies.

Figure 6.13 ▶ Road-rail modal split in EU Member States, 2006



Source: Eurostat.

Key point

The proportion of surface freight transported by road and by rail varies widely between countries.

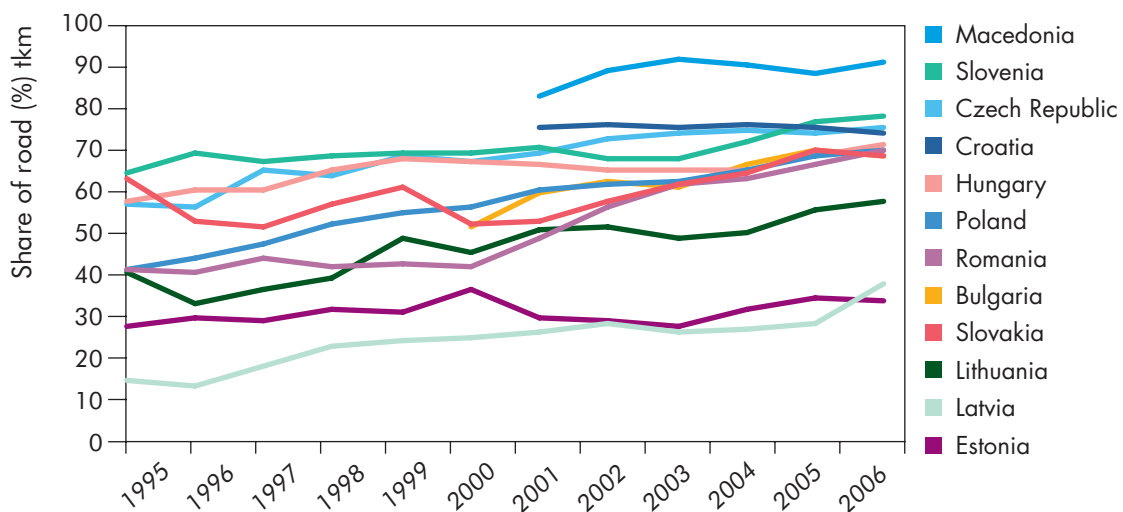
Trucking is increasing its share of the worldwide surface freight market, although at different rates in different countries. In the countries of Central and Eastern

Europe, for example, the transformation from planned to market economies and heavy investment in road infrastructure has caused a major switch from rail to road (Figure 6.14). In China, a slower shift from rail to trucks means that, although rail remains the dominant mode of surface freight movement at least in the short run, rail's share of the freight volumes declined from 76% to 69% between 1990 and 2006.

The shift to road can be attributed to a range of factors, particularly:

- More investment in and upgrading of the road infrastructure than the rail infrastructure in many countries.
- The liberalisation of road freight markets and the removal of regulatory protections afforded to rail by quantitative licensing and tariff restrictions.
- Increases in the maximum permitted size and weight of trucks.
- Changes in industrial structure, especially the shift from primary production to manufacturing in many developed countries. Rail commands a much smaller share of the freight market in lighter, higher value manufactured goods.
- Change in the primary energy mix. In some countries, a switch away from coal has deprived rail of one of its main bulk transport opportunities.
- The move to more flexible or just-in-time manufacturing. The intrinsic inflexibility and slower speed of rail freight services make them less suited to such approaches.

Figure 6.14 ▶ Road share of inland freight transport in Central/Eastern Europe, 1995-2006



Note: Includes road, rail and inland waterway.

Source: Eurostat.

Key point

The transformation from planned to market economies, coupled with heavy investment in road infrastructure, has caused a shift from rail to road in Central/Eastern Europe.

Many of the new production and distribution facilities constructed over the past few decades have been located too far from railway lines to permit direct access. To capture freight traffic in these situations, rail companies must develop intermodal services that link the rail network to local road networks. In some parts of the world, intermodal services have been one of the main growth sectors in the rail freight market.

The main growth in intermodal transport has been in containers and trailers, rather than in the movement of complete vehicles. Intermodal traffic has been rising steeply in both the European Union and the United States, with total tonnage in the United States increasing by 16% between 2002 and 2006 – and predicted to grow by a further 73% by 2035 (Federal Highway Administration, 2008).

Vehicle utilisation



Very little published data exists on the utilisation of road freight vehicles and almost none on the loading of freight trains. A small number of countries, including the United Kingdom, Germany and France, have undertaken surveys to estimate the proportion of vehicle capacities (measured by weight, cubic volume or deck area) occupied by a load. Most of the available data for road transport are compiled by EU Member States and published by Eurostat. These statistics on the distances that trucks run empty and laden can be used to calculate the average payload weight on laden trips and the percentages of the total distance that are travelled empty.

Despite the lack of evidence, it is generally accepted that the average density of freight moved by surface modes is declining in many developed countries, particularly as products increasingly use lighter materials and as a result of the greater use of packaging. This is increasing the proportion of loads that become physically full before they reach their weight limits. Official freight surveys of surface freight transport usually measure only the weight of goods moved. They can also contain anomalies, by for example considering vehicles to be loaded even when they are carrying empty containers or handling units such as pallets.

Another issue with measuring vehicle utilisation is that load weights are typically the basis for measuring efficiency. But as freight shifts toward higher value but lighter loads, weight-based efficiency may deteriorate at the same time as the value per unit of energy used improves. Value is the better unit of measurement, since it reflects society's preferences: moving 1 t of computers is a more valuable and more societally efficient way to use a given amount of trucking energy than moving 1 t of bricks. But, unfortunately, value-based efficiency data are rarely available. In general, trucks are most efficient in terms of tkms per unit of fuel consumed when they move as much weight as they can, rather than travelling partly full or empty. So weight is still a useful metric to compare the efficiency of different transport options.

Empty running of trucks

To maximise the efficient use of trucks, it is important to minimise the distances they travel empty. Empty travel may average as much as 50% of all truck travel in some countries. In Europe, where it has generally dropped over time, it averages from 15% to 35% depending on the country, with an overall average around 25%. National variations reflect differences in the sizes of countries, the nature of their freight markets, regulatory controls and regional imbalances in freight flows. The longer a haul, the greater in general is the financial incentive to find a paying load for the return journey. In larger countries, therefore, the level of empty running tends to be lower. Road haulage companies in the United Kingdom, for example, have an average haul length of 101 kms and on average run 27% of their kilometres empty. By contrast, in 2007 one of the largest carriers in the United States (J.B. Hunt) had an average trip length of 832 km and an average empty running figure of only 12% (Anon, 2008).

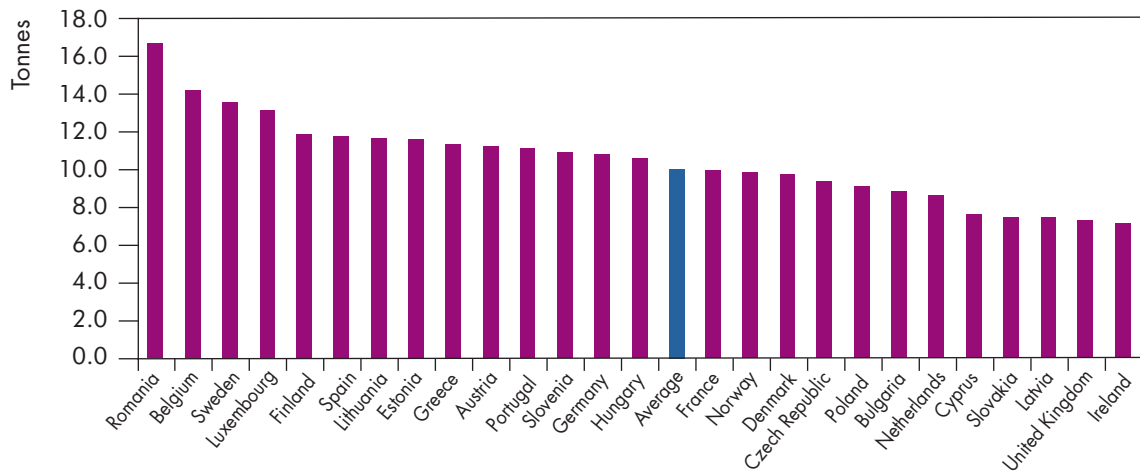
Reductions in empty running over time are likely for several reasons, including: the development of load-matching agencies and online freight exchanges; the strengthening flow of products going back along the supply chain for recycling and remanufacture; backloading initiatives by retailers and manufacturers; and the outsourcing of transport to third-party carriers with multiple loading options. In a recent Delphi survey, 100 logistics specialists in the United Kingdom forecast that the overall level of empty running in the country would drop from 27% to 22% by 2020 (Piecny and McKinnon, 2008).

Trends in load weights and capacity use

The average truck payload weight in the European Union is 10 t. The average varies between Member States from 7 t to 16 t (Figure 6.15). There is no obvious explanation for this wide variation, though differences in data collection and reporting practices may explain some of it. It also probably reflects differences in industrial structure, trading practices, past and present vehicle size and weight regulations, the nature and level of transport outsourcing, and the role of wholesalers and retailers in the distribution chain.

In 14 of the 24 countries for which data is available, the average payload weight rose by 5% between 2004 and 2007. The recent United Kingdom Delphi survey predicted that the average payload weight in trucks would increase by about 10% by 2020. In some countries and for some categories of truck, average loads can continue to rise only if there is a relaxation of existing operational constraints and regulations on vehicle loading.

Few large-scale surveys have been conducted to assess the proportion of the available carrying capacity that is actually utilised. The Transport KPI benchmarking surveys conducted in the United Kingdom in seven sectors over the past ten years probably represent the largest and most diverse source of such data. Figure 6.16 shows the variation in average vehicle utilisation across 53 fleets comprising over 3 000 vehicles in the United Kingdom food supply sector, measured in terms of both weight and pallet loads. On average on all laden trips in the sector, 53% of the available weight carrying capacity and 69% of the available pallet slots were used.

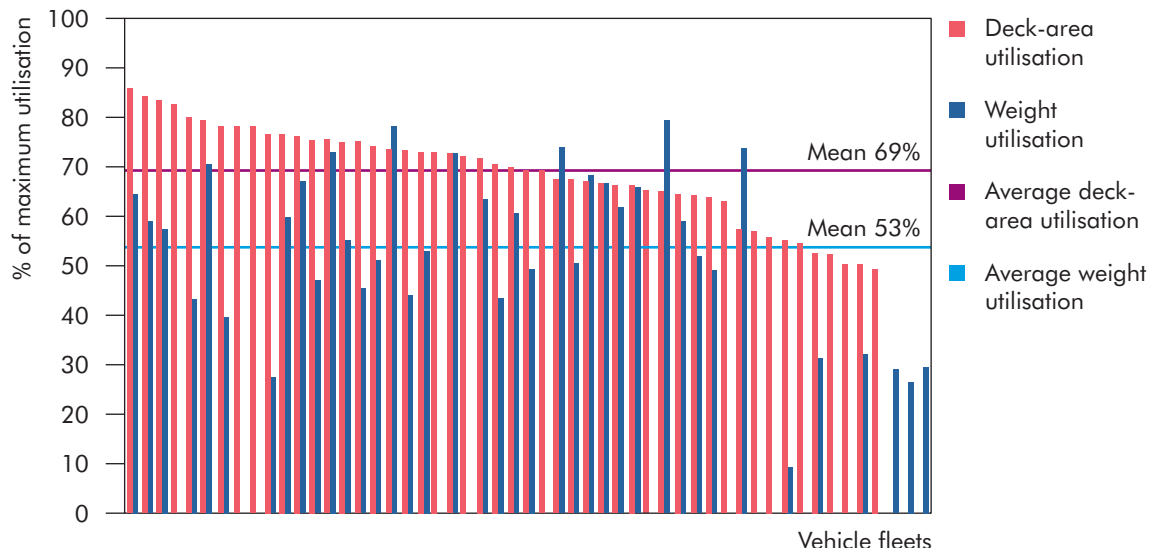
Figure 6.15 ▶ Trend in average payload weight on laden trips in Europe, 2006

Source: Eurostat.

Key point

The average truck payload weight on laden trips in the European Union is 10 t, with a wide variation across countries.

The survey also revealed wide variations in vehicle loadings even within reasonably homogeneous industry sub-sectors. Similar observations have been made in other sectors, such as non-food retailing, automotive and express parcels. This limited evidence suggests that significant potential exists in the United Kingdom to increase vehicle loading in the road freight sector.

Figure 6.16 ▶ Variations in mean weight and deck-area utilisation of 53 United Kingdom truck fleets operating in the food supply chain, laden trips

Source: McKinnon *et al.*, 2003.

Key point

Wide variations in vehicle loadings exist, even within reasonably homogeneous industry sub-sectors.

Vehicle loading is affected by numerous factors, including:

- **Demand fluctuations:** Vehicles that are acquired with sufficient space or weight to accommodate peak loads inevitably spend much of their time running with spare capacity.
- **Just-in-time delivery:** Companies are often prepared to sacrifice transport efficiency to achieve large reductions in inventory and other productivity benefits.
- **Unreliability of delivery schedules:** Where schedules are unreliable, return loads or higher degrees of load consolidation can be difficult to achieve.
- **Vehicle size and weight restrictions:** Some loads reach the maximum weight limit before all the space in the vehicle is occupied, while other low-density loads exhaust the available space before the legal weight limit is reached. This results in under-utilisation of the vehicle in terms of either volume or weight.
- **Handling requirements:** Many companies are prepared to compromise vehicle utilisation to increase the speed and efficiency of the loading and unloading operations. The roll-cages widely used in supermarket distribution, for example, can substantially reduce handling times and costs but at the expense of 15% to 20% of the vehicle fill.
- **Capacity constraints at company premises:** Limited storage capacity at either the origin or the destination of a trip can constrain the vehicle loading. Tanks and silos at farms or factories, for example, may not be able to hold a full truck load. Many retailers have compressed storeroom areas to maximise the front-of-shop sales floor.
- **Poor co-ordination of the purchasing, sales and logistics functions:** Opportunities for securing return loads are seldom discussed in the context of trade negotiations between companies. Sales staff may also be incentivised to make delivery commitments to customers, which entail the transport of part-loads.

Increases in the real cost of transport are forcing companies to pay greater attention to maximising vehicle capacity. These changes are tilting cost trade-offs in favour of increased transport efficiency and supporting the economic case for greater investment in fleet management tools and ICT. Several developments have gathered momentum, mainly in developed countries, which can help companies achieve a step change in vehicle utilisation. These include:

- **Web-based procurement of freight transport services:** An increasing proportion of freight services are being purchased online, mainly in Europe and North America, either through auction sites or, on a longer term basis, using web-enabled tendering platforms. This permits better matching of freight flows with available capacity, and is increasing the levels of loading on return trips. One large European freight exchange has claimed that its clients were achieving an average reduction in empty running of around 7% (Mansell, 2004). The integration of optimiser software into these trading platforms and the pre-consolidation of several shippers' demands is further increasing the efficiency gains.
- **Collaborative initiatives designed to improve the utilisation of logistics assets:** Major initiatives are underway in sectors such as fast-moving consumer goods and chemicals to promote the pooling of transport demands to achieve greater load

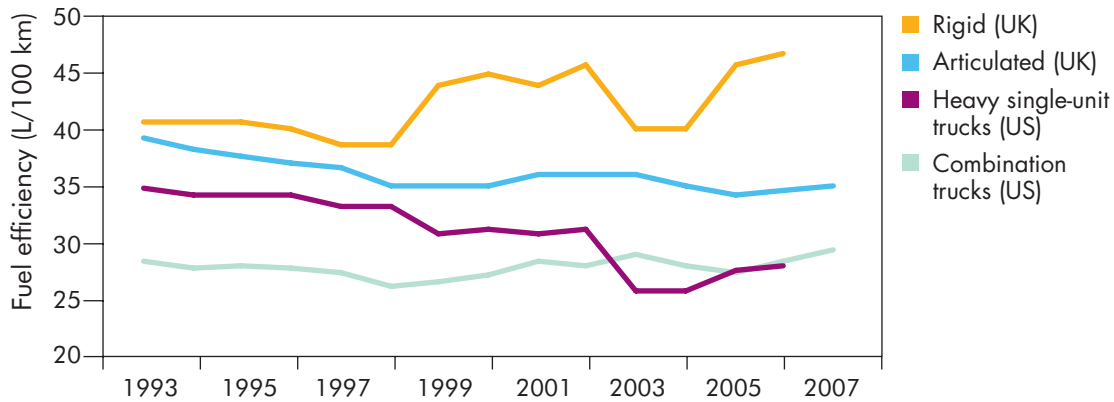
consolidation and reduced empty running (Mason *et al*, 2007). For example, a group of major food manufacturers and distributors in the United Kingdom, under the auspices of ECR UK, set themselves the target of saving 48 million truck-miles in 2008 by sharing vehicles and promoting more efficient warehousing networks. The European chemical industry is also encouraging inter-company collaboration to maximise utilisation of logistics assets and avoid unnecessary journeys. These initiatives are often taken in association with logistics service providers.

- **Greater sharing of information between shippers, carriers and customers:** More open exchange of information and joint planning of transport operations among these links in the logistics chain has been shown to improve vehicle load factors and cut empty running. In North America, this is known as collaborative transportation management (CTM). United States carriers that have managed to extend their planning horizon as a result of CTM have increased the utilisation of their regional truck fleets by between 10% and 42%, mainly as a result of securing improved return loadings (Esper and Williams, 2003).
- **Vehicle routing and scheduling software and tele-matics:** Computerised vehicle routing and scheduling (CVRS) software helps companies to optimise the use of their vehicles with respect to various metrics, including distance travelled, driving time, vehicle loading and cost. Several of these metrics correlate closely with fuel efficiency. Fuel savings from the use of CVRS depends on the complexity and variability of the delivery operation and the standard of the previous manual route and load planning. Fuel savings of around 5% to 8% have been quoted (Department for Transport, 2005). Linking CVRS with GPS-based vehicle tele-matics systems can increase the potential savings. Over the past decade, a new generation of higher-level modelling tools have been developed to optimise complex freight transport networks. Although these tools are calibrated mainly to minimise total transport costs or increase revenues, this generally results in cutting fuel consumption by a significant margin.

Vehicle efficiency

The efficiency of vehicles has a large impact on the energy use and CO₂ emissions attributable to freight movement. Although data is poor for many countries, the available evidence on trends in truck efficiency shows a mixed picture. Figure 6.17 shows the trends for two classes of vehicle, rigid (single unit trucks) and articulated (cab/trailer combination trucks) in the United Kingdom and the United States since 1993. It suggests that the fuel efficiency of rigid vehicles in the United Kingdom and single-unit trucks in the United States has been increasing, that the fuel efficiency of combination trucks in the United States has been declining erratically, and that the fuel efficiency of articulated vehicles in the United Kingdom has remained stable. These average figures, however, can hide trends in the size and weight distribution of vehicles within the broad rigid and articulated categories. Also, over the period in question, the maximum weights and dimensions of vehicles have changed. As vehicles get larger and/or are more heavily loaded, their energy use per kilometre will rise, although their energy use per tkm may decline.

Figure 6.17 ▶ Fuel efficiency of trucks in the United Kingdom and United States 1993-2007



Sources: UK Department for Transport; Davis et al., 2008.

Key point

The fuel efficiency of different vehicle types in the United Kingdom and in the United States did not evolve consistently in the past 15 years.

Figure 6.18 shows, for a 40-t, 5-axle vehicle, how energy use per tkm drops sharply as the vehicle payload increases. Although this benefit starts to slow around 10 t, it still improves. For example, about half as much energy per tonne is used for a 25-t load as for a 10-t load. The upper blue line shows energy use per truck-kilometre. With a 10-t load, a truck uses around 250 g of fuel per km; with a 25-t load, this increases to 320 g per kilometre. If the 25-t load was moved in 2.5 loads of 10-t each, the total energy requirement would be 625 g of fuel per km, i.e. nearly double that needed by one large truck.

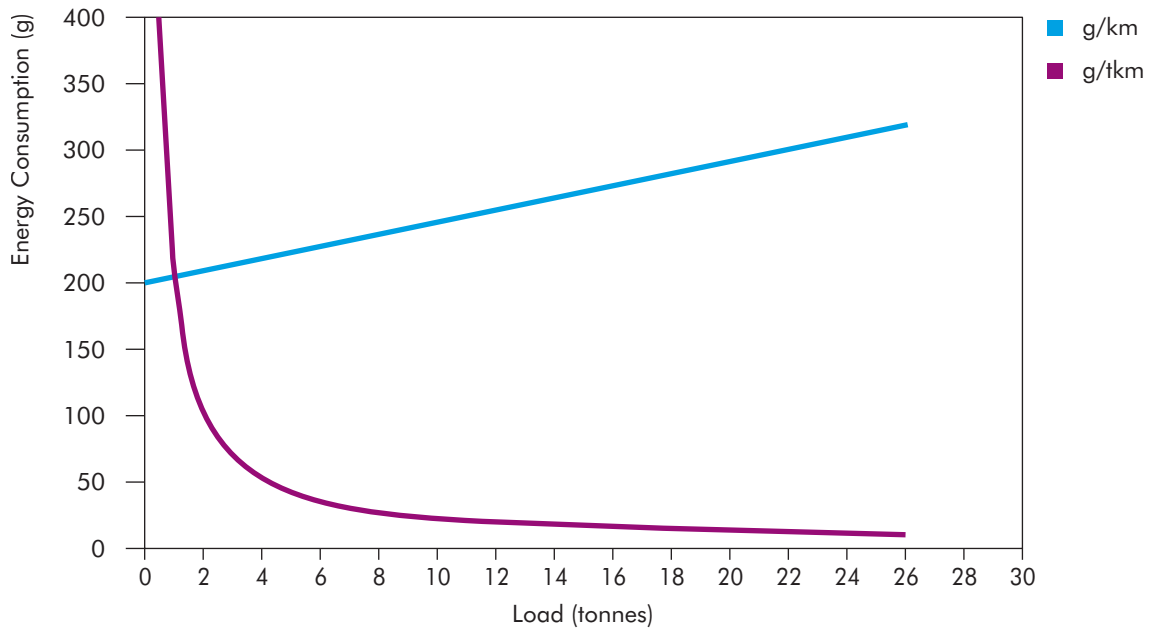
Increasing the maximum allowable weight of laden vehicles on the road can therefore be expected to yield efficiency improvements per tkm, although clearly the benefits decline in percentage terms for each extra tonne of increase.

The fuel economy of similar sized trucks, even trucks used for very similar purposes in the same industry, can vary widely. Research in Finland (Nylund and Erkkila, 2007) has found variations of 5% to 15% in the fuel efficiency of different brands of the same types of new truck.

The average truck efficiencies of individual truck fleets vary even more widely than national averages, as shown by efficiency benchmarking surveys in the United Kingdom, Germany and Canada. Figure 6.19 shows the variations in average fuel consumption for vehicles of particular weights and types in 53 fleets engaged in moving food products. The degree of variability among lighter, rigid trucks is even greater than that between heavier, articulated vehicles.

This benchmarking reveals wide inter-fleet variations in fuel efficiency, even within particular sub-sectors.

Figure 6.18 ▶ Relationship between fuel efficiency/energy intensity and payload weight in a 40-tonne, 5-axis truck

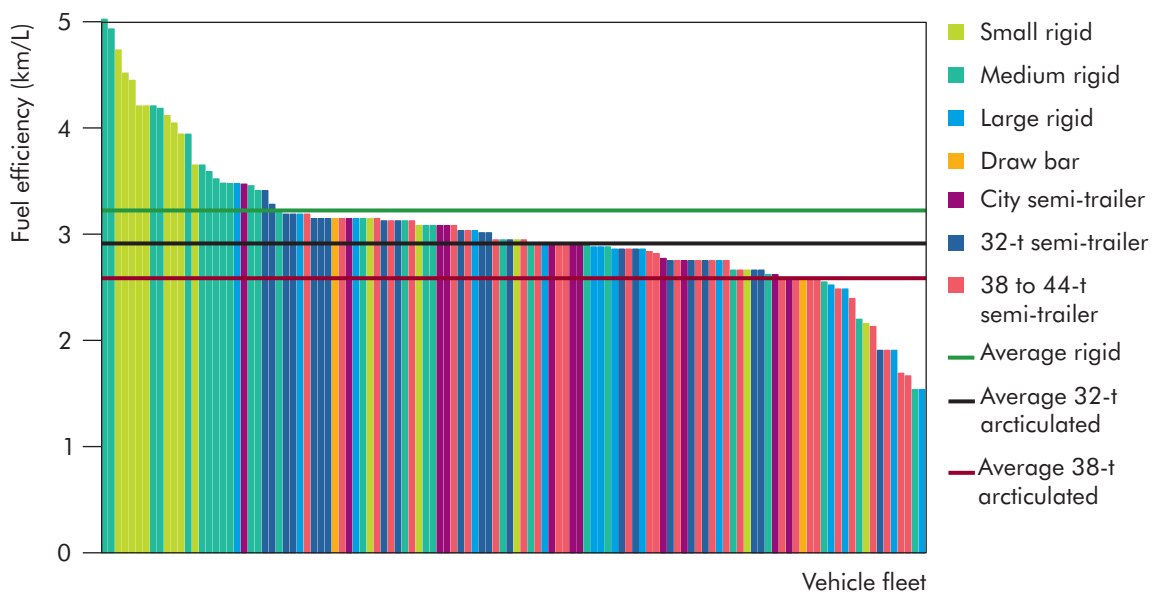


Source: IFEU, 2008.

Key point

Energy use per tkm drops sharply as the vehicle payload increases.

Figure 6.19 ▶ Variations in the average fuel efficiency of trucks engaged in the distribution of food products



Source: UK Transport KPI programme – McKinnon, 2003.

Key point

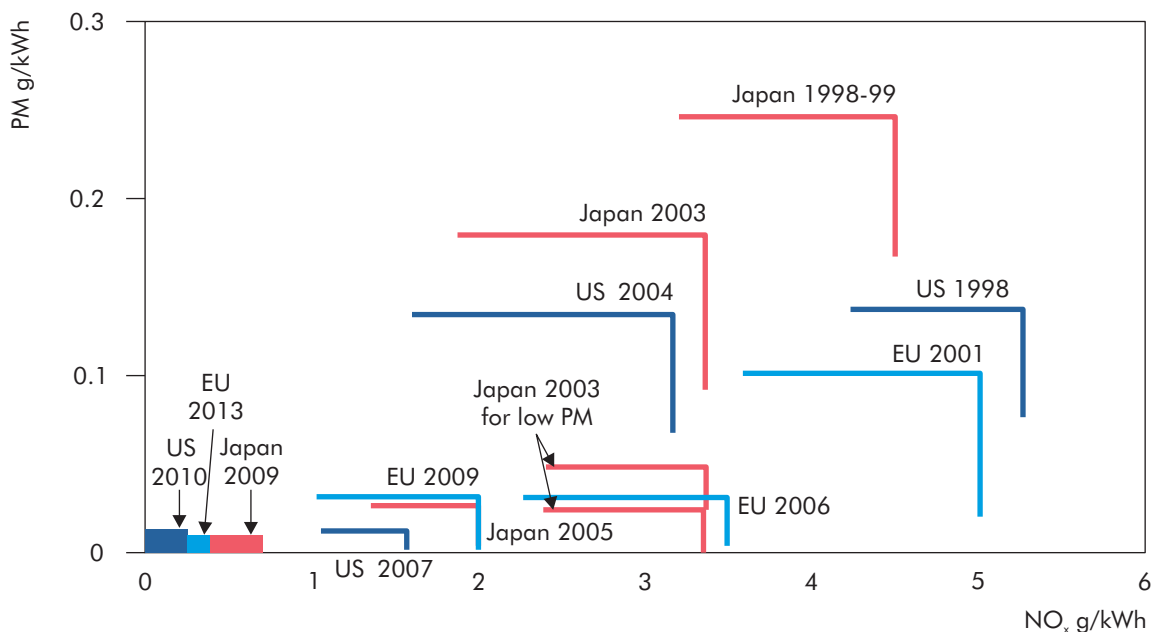
There is a wide degree of variability among the average fuel efficiency of different rigid trucks (lighter) and articulated vehicles (heavier).

An earlier KPI benchmarking survey in the UK food sector suggested that raising the energy efficiency of all below-average performing fleets to the sub-sectoral mean would cut total fuel use by 5%, and raising it to the mean of the top third of fleets would yield a 19% fuel saving (McKinnon and Ge, 2005). Surveys of trucking operations in the United States (SmartWay), Canada (Fleet Smart) and Germany (Leonardi and Baumgarten, 2005) confirm that substantial savings in fuel would be possible if all fleets were to become as energy efficient as those of the best practice operators.

Opportunities for improving the fuel efficiency of trucking operations

Over the past 40 years, the average fuel efficiency of new trucks has been improving at a rate of around 0.8% to 1% per annum (IEA, 2007a). The main improvements were made in the 1970s and 1980s. Since the early 1990s, the rate of fuel efficiency improvement has been much slower, mainly because truck manufacturers have had to meet tightening emission standards, particularly for NO_x . It has been estimated that if these controls had not been imposed, average truck fuel efficiency would have been higher today by around 7% to 10%. One estimate for the United States trucking industry puts this fuel penalty at 15% to 20% over the period 1988 to 2010.

Figure 6.20 ► NO_x and PM regulations in United States, the European Union and Japan



Key point

Pollutant emission regulations for trucks have tightened over time in all OECD regions.

Achieving further improvements in local air quality is likely to continue to conflict with efforts to cut fuel consumption and CO₂ levels, because the control of some pollutants imposes the use of instruments that can lead to consumption increases (e.g. particulate filters, which need regeneration at the expense of fuel use). Measures to control NO_x, which can include lower combustion temperatures and various after-treatment systems, tend to reduce engine efficiency. Figure 6.20 shows how the NO_x and particulate (PM) regulations in the United States, the European Union and Japan have tightened over time (moving down for tighter PM controls and to the left for tighter NO_x controls). The Japanese 2009 regulation, the US 2010 regulation and the EU 2013 regulations (Euro VI) appear likely to require changes in engine technologies that would have further negative impacts on fuel economy.

There remains significant potential to improve the fuel efficiency of trucks even within a tight emissions regime. Much of the improvement in vehicle economy over the next decade is likely to come from the wider diffusion of existing and proven technologies, such as aerodynamic profiling, automatic transmissions and idling-control devices. Other technologies will also contribute, especially over the long term. The *ETP 2008* estimate of a potential for a 40% reduction in fuel use per tkm through the full adoption of available technologies may even underestimate the potential. Still further savings may be achieved from changes in powertrains, aerodynamics, tyres, and weights and dimensions, as discussed below.

Powertrain efficiency improvements

Truck powertrains already rely almost exclusively on relatively efficient diesel engines, but further significant improvements to today's vehicles may still be possible. For example in the United States, where the thermal efficiency⁶ of truck engines is currently around 40% to 42%, this could potentially be raised to 50% or even 55% (US National Research Council, 2008). This would require the application of a range of incremental technologies affecting different aspects of the vehicle's design and operation, including the recovery of energy from exhaust gases and hybridisation.

Energy can be recovered from exhaust gases in several ways. Turbo charging (or turbo-compounding) involves the recycling of exhaust gases to recover heat energy that would otherwise be lost through the exhaust system. This can allow the engine rating and fuel consumption to be reduced for a given power rating and enable fuel savings of 2.5% to 5%. Turbo-charged engines are currently available in Europe and Japan, though there has so far been limited uptake of this technology. The use of combined heat and power systems, such as the bottoming cycle, in trucks can also cut fuel consumption although this is at an early stage in its development and is unlikely to be commercialised for at least another decade.

Most large truck manufacturers are now developing electric hybrid engines for rigid vehicles and several hundred such trucks are currently in service. As the potential fuel savings from hybridisation are closely correlated with the frequency of stops and starts, the technology is well suited to the multiple drop and collection rounds

6. The thermal efficiency of a vehicle engine is the ratio of the amount of propulsion it produces relative to the available heat energy in the fuel that it burns.

that rigid vehicles normally undertake. Average fuel savings of 25% to 30% are being achieved by these vehicles on typical duty cycles.

Until recently, it was considered that hybridisation would have very little application in the long-haul operations of articulated vehicles, since most transport is on motorways rather than in urban stop-and-go driving situations, where hybrids provide their main benefit. It has been estimated that fuel savings of 5% to 7% may be achieved in some of the delivery operations that long-haul vehicles undertake, but much larger savings would be likely on vehicles that are subject to frequent braking, such as those used to move containers in and around ports, refuse trucks, or LCVs and medium trucks operating in urban environments.

Hydraulic hybrid engines are also under development. A prototype is being tested by the parcel carrier UPS. It features a hydraulic drivetrain that replaces a conventional drivetrain and eliminates the need for a conventional transmission. According to the US EPA, this vehicle demonstrates the most efficient heavy-duty powertrain yet developed, achieving 40% reductions in CO₂ emissions (EPA, 2004 and 2006). Testing of a similar technology (developed by Bosch-Rexroth) for refuse trucks has also been undertaken by the New York City's Department of Sanitation (Bosch-Rexroth, 2009). According to Bosch Rexroth, the hydrostatic regenerative braking (HRB) technology has already undergone field testing in urban settings, with positive results. The system has been claimed to reduce fuel consumption by up to 25%, but the actual results are significantly dependent on the braking frequency (GreenCarCongress, 2008).

Non-powertrain efficiency improvements

A range of non-powertrain improvements are available to cut the energy use of trucks in operation. Major options are outlined below.

Auxiliary equipment efficiency: Improving the energy efficiency of the auxiliary equipment on vehicles (such as pumps, fans, air compressors, and heating, air-conditioning and power-steering systems) can save significant amounts of fuel. The installation of separate power systems designed for auxiliary loads can also save fuel, as it decouples their operation from that of the main vehicle engine, which is designed for much larger loads. Separate batteries and plug-in electric systems can be used for more efficiently providing auxiliary power. In some applications, energy efficiency gains of up to 50% can be achieved in these auxiliary systems by powering them separately (IEA, 2007a).

Technological driving aids and constraints: Anti-idling devices automatically switch off the engine when the vehicle has not been moving for a specified period. Smart cruise control can use GPS to anticipate the topography of the road ahead and manage the braking and acceleration of the vehicle more effectively than the average driver can. This improves fuel efficiency. Vehicle speed can also be controlled by engine governors. In the European Union and Japan, the installation of engine governors set at a maximum speed of 90 km/h are now mandatory for most types of trucks. In the United States their use is optional.

Aerodynamic improvements: In most countries, trailer technology has lagged behind the technical development of tractor units, partly because trailers generally

have a longer life span but often because they are owned by the shippers, who do not have direct responsibility for the transport operation. As awareness of the contribution of trailer design to fuel efficiency spreads, there is likely to be a more rapid uptake of trailer innovations.

It has recently been discovered that improved profiling of the rear of trailers can have a significant impact on fuel efficiency. In the United States, the addition of 'boat tails' to the back of trailers has been shown to raise the fuel efficiency of Class 8 trucks by up to 10% (GreenCarCongress, 2008). In the United Kingdom, 'teardrop' trailers, which slope downwards at the front and rear, are now being adopted by major retailers and have been shown in independent tests to cut fuel consumption by 10% when compared to a conventionally shaped trailer (Banner, 2008). The UK Climate Change Committee (2008) estimates that around 50% of the potential non-powertrain savings in CO₂ emissions from heavy goods vehicles in the United Kingdom could come from the use of teardrop trailers.

Participants at an IEA workshop (IEA, 2007a) indicated that improved aerodynamics could represent 10% to 20% of all potential fuel efficiency improvements to the heavy-duty truck fleet, with most of the benefits accruing to larger articulated vehicles making high-speed, long-distance trips. Many of the changes that would be needed can be retrofitted to vehicles and so their rate of adoption is not constrained by the vehicle replacement cycle. Up to 85% of the potential fuel savings from improved aerodynamics come from trailer design, particularly in the case of taller vehicles.

Improved tyre performance: The rolling resistance (RR) of tyres accounts for approximately 8% to 10% of the energy used in running a heavy truck at average speed. Efforts are being made to reduce this RR without compromising vehicle braking and safety. One way in which this has been achieved is through the use of extra wide tyres rather than pairs of tyres. The weight of the tyres is also reduced. The next generation of tyres with lower RR may yield fuel savings of 3.5% to 8%, with the largest benefit accruing to larger trucks making long hauls at high speeds. The under-inflation of tyres also wastes fuel. This can be corrected by the introduction of tyre pressure monitoring systems and automated tyre inflation.

Vehicle weights and dimensions

Reducing the weight of vehicles normally reduces fuel use. Although for trucks the weight of the empty vehicle may represent only a small fraction of the average loaded weight, some weight reduction opportunities seem worth pursuing.

Trucks with similar capacities can have very different empty weights. For example a recent German study of trucks with a 40-t capacity found an average empty weight of 14 t, but a minimum empty weight of only 11 t (Leonardi and Baumgartner, 2004). Lightweighting of the vehicle through the use of less dense materials, such as aluminium and carbon fibre, and the removal of unnecessary fittings can significantly cut the empty weight. Research in the United States, however, suggests that the resulting average fuel savings are likely to be relatively modest, at roughly 0.5% for each 450 kg of weight reduced (Southwest Research Institute, 2008).

The energy efficiency of road freight operations can be increased by a much a greater margin if governments were to allow trucks to carry heavier loads. The current generation of trucks could carry heavier weights without increasing engine brake-horsepower. As a result of the increase in maximum truck weight in the United Kingdom, from 41 t to 44 t in 2001, it is estimated that total fuel consumption per tkm moved by trucks in the heaviest class was around 1.5% lower in 2003. Raising the maximum weight of a fully-laden Class 8 truck in the United States, from 36.1 t to 44 t, would increase tkm/L by 17% at full load, even allowing for an increase in axle numbers from five to six (Greszler, 2008). The standard gross weight limit on United States Class 8 trucks is relatively low by European standards, where most countries impose a limit in line with the EU cross-border restriction of 40 t, but some countries have adopted 44 t, 50 t or even 60 t limits.

As a large and increasing proportion of loads are constrained by volume rather than weight, the fuel savings from a relaxation of gross weight limits can be augmented by an increase in the maximum size of vehicles. The longer and heavier vehicles that are permitted to run in Sweden – at a maximum length of 25.5 m and maximum weight of 60 t when fully laden – consume 15% less fuel per tkm than a 16.5 m, 40 t truck (TFK, 2002). Proposals to extend the maximum length of trucks are very controversial, however, mainly because of concerns about safety, the capacity of the road infrastructure to accommodate them, and the potential diversion of freight traffic from rail and water-borne services. The German and United Kingdom governments have recently rejected the case for 25.5 m trucks, although they have been approved in the Netherlands. In the United Kingdom, where bridge and tunnel clearances are relatively high, companies have been able to gain additional cubic capacity vertically rather than horizontally. By double decking their trailers, they have been able to increase the number of pallet-loads carried, resulting in energy efficiency improvements of 60% to 100% in volumes carried per litre of fuel.

Non-technology efficiency measures

Trucks can be prevented from operating at optimum fuel efficiency by a wide range of technical imperfections. Good maintenance is important. Typical defects include poor combustion, fuel leaks, under-inflated tyres and axle misalignment. Such problems can now be detected, often on a real-time basis, by on-board diagnostics. This reduces dependence on driver reporting and intermittent workshop tests. Vehicle manufacturers are also providing diagnostics and maintenance as value-adding services at the time of purchase, much of which is directed at maximising the fuel performance of trucks. By 2015-2020, continuous monitoring of truck fuel efficiency and fine-tuning of fuel performance will be the norm in developed countries.

Driver behaviour can also affect efficiency. Driver training programmes have been shown to improve fuel efficiency by as much as 15% (IEA, 2007b) although, without measures to incentivise the maintenance of these learned good habits, the impact generally declines over time. Truck simulators have been used to provide training in safe and fuel-efficient driving techniques, though doubts have been expressed about their relative cost-effectiveness. To derive longer-term benefit from training

in efficient driving skills, companies are increasingly introducing incentive schemes, although it can be difficult to implement them in a manner that is fair and consistent to drivers. Installing in-car equipment, such as gear shift indicators, cruise control and on-board fuel economy computers, can also help.

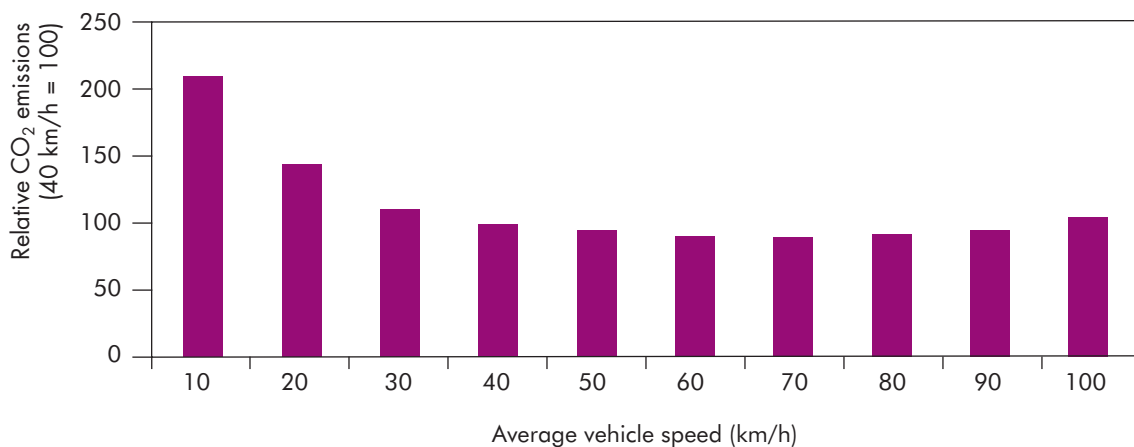
A Japanese Eco-driving Management System programme aims to promote more efficient driving through the combination of driver education and the use of sophisticated digital tachograph-like devices and tele-matics (Onoda *et al.*, 2007). Thirteen transportation companies participating in the programme in 2006 showed an average improvement of 8% in energy consumption and CO₂ reductions, with a maximum of 20%.

Effects of traffic congestion on fuel efficiency

Worsening traffic congestion on road networks will tend to frustrate efforts to improve the average fuel efficiency of road-haulage operations. Research in Germany has indicated that stop-start truck driving in congested traffic conditions can sharply increase the amount of fuel consumed (VDA, quoted by ACEA, 2009). A truck that would use 28 L/100 km at 50 km/h without stopping would use 52 L/100km if it stops once every kilometre, and 84 L/100km if it stops twice every kilometre. Road-charging systems that charge higher prices at peak periods to reduce congestion could thus save a considerable amount of fuel in trucks as well as cars.

The Japanese Automotive Manufacturers Association has conducted a study of fuel use and CO₂ emissions associated with different vehicle speeds. Figure 6.21 shows strongly increasing rates of CO₂ emissions below an average speed of about 40 km/h and also above an average speed of 90 km/h in the case of passenger vehicles. A similar trend shall be imagined for heavy-duty vehicles.

Figure 6.21 ► CO₂ emissions at different vehicle average speeds



Source: JAMA, 2008.

Key point

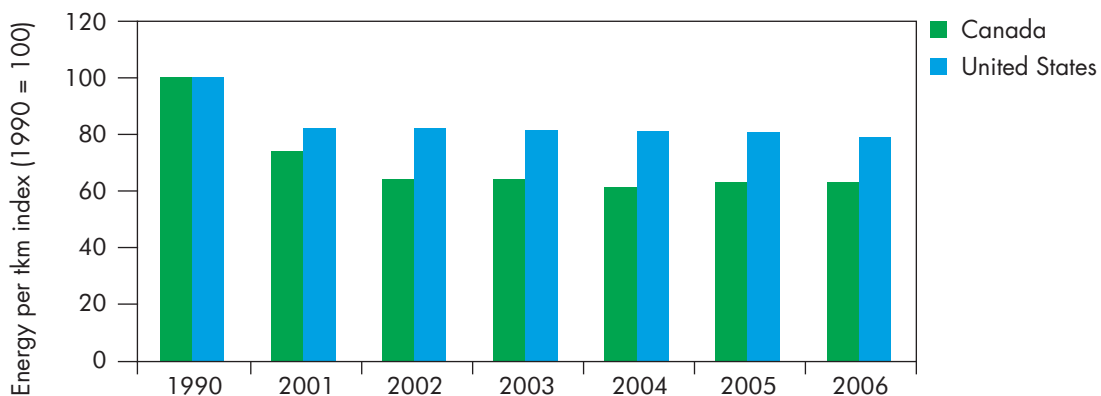
The rates of CO₂ emissions change in relation to average vehicle speeds.

The exposure of road-haulage operations to traffic congestion could be reduced by rescheduling deliveries away from peak periods, e.g. into the evening or night. In some countries, an increasing proportion of truck-running is now done in off-peak periods. In the United Kingdom, for example, truck running between 8 p.m. and 6 a.m. increased from 8.5% of all running by distance in 1985 to 19% in 2005 (Black *et al.*, 1995; Dept for Transport, 2007). The imposition of night curfews on freight deliveries in towns and cities constrains night-time operation, although as trucks become quieter the justification for these restrictions weakens.

Energy intensity of rail freight operations

Data on rail efficiency are available for only a few countries. The available data indicate that, on average, rail systems are significantly more energy efficient at moving freight than almost any other motorised mode. But the range of efficiency is wide. IFEU (2008) report nearly 300% variations in diesel traction efficiencies, from 2.6 g to 9.7 g of fuel per gross-tkm. Figure 6.22 shows the trends in energy intensity in US and Canadian rail freight operations, suggesting that there has been a significant improvement in energy efficiency since 1990, but only marginal gains since 2001. It is not known how representative these trends are of rail freight operations in other parts of the world. For example, it is estimated that in Spain the average energy intensity of rail freight operations was almost identical in 1990 and 2004, at 0.4 MJ/tkm (Pérez-Martínez, 2007).

Figure 6.22 ▶ Energy intensity of rail freight operations in North America



Sources: Elaboration from Transport Canada, 2008; Association of American Railroads, 2007.

Key point

Rail freight energy intensity has improved significantly since 1990, but only marginally after 2001.

The share of rail freight hauled in different countries by electric engines varies widely, and is likely to increase in future. This will allow rail freight transport to strengthen its CO₂ advantage over road as electricity generation switches to renewable energy sources and nuclear power.

Opportunities for reducing the energy intensity of rail freight operations

The energy intensity of rail freight operations can be reduced in a number of ways:

- **Upgrading locomotive fleets** to newer, more energy efficient engines. The switch from Class 57 to Class 66 locomotives in the United Kingdom, for example, increased average fuel efficiency by around 15%. The energy efficiency of new locomotives is steadily rising, although for diesel engines, as for trucks, this is being partly constrained by tightening emission controls, particularly on sulphur. Locomotives also tend to have long working lives and long depreciation periods, which discourage early investment in replacement stock.
- **Electrification:** the switch from diesel to electricity allows a gain in efficiency close to 15% on a life-cycle basis because of the lower energy losses occurring in power plants rather than in ICEs, combined with the opportunity to use regenerative braking and to minimise idling. It also offers the potential to decarbonise substantially rail operations in countries with low-GHG electricity generation.
- **Reducing the weight of rolling stock:** significant potential exists to reduce the empty weight of rail rolling stock, although as with trucks the benefits depend on how much weight is being carried. Since 2001 in the Netherlands, the Dutch rail agency NS Reizigers has fixed a maximum weight for new stock and offered an incentive for suppliers to reduce the weight of stock in the form of a bonus for each kg of weight reduction below that maximum value (Van Dongen *et al.*, 2000).
- **Increasing the maximum train size** and maximum weight of rolling stock can also help. The double-stacking of container trains, as in the United States, offers a step-change improvement in energy efficiency. In some countries, such as the United Kingdom, tight track clearances constrain the size of rolling stock and substantial investment in rail infrastructure would be needed to avoid these. The weight-bearing limits on railway tracks also vary internationally.
- **Increasing the load factor of rolling stock** may increase efficiency in some countries.
- **Driver behaviour:** experience in Germany shows that drivers can be trained and incentivised to drive trains more fuel efficiently. Greater automation of locomotives over the next few decades will further improve energy efficiency.
- **Overhauling operating practices** to reduce idling, adopting more efficient systems for the repositioning of locomotives, and improving locomotive and rolling stock maintenance will also improve efficiency.

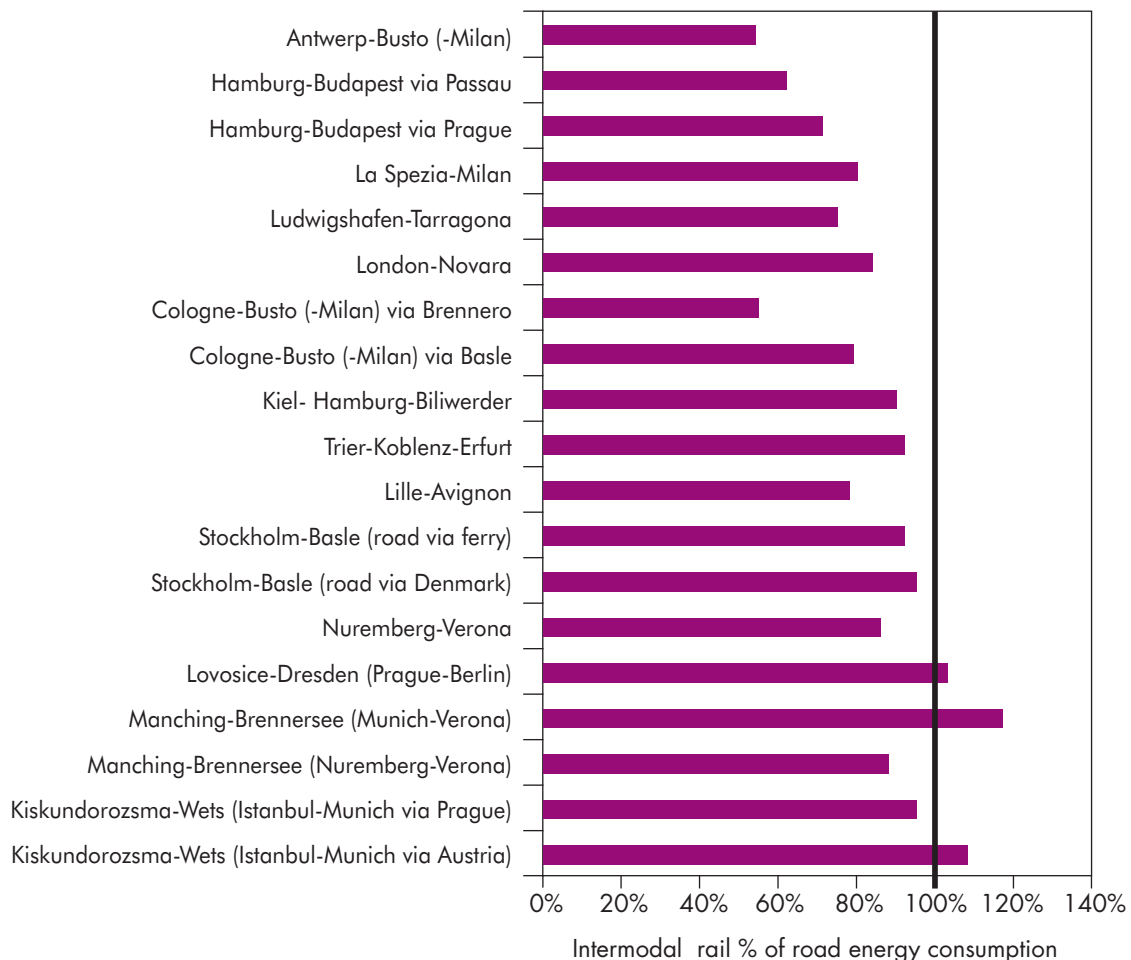
Road-rail intermodal operations

Intermodal operations, which use multiple transport modes to move containerised freight and involve no handling of the freight when switching from one mode to another, can help ensure that the most energy efficient modes are used for different stages of the movement of freight. But the net energy efficiency impacts of intermodal activities are unclear, once the energy used in the intermodal transfers themselves are

taken into account. Only limited data is available on the energy intensity of intermodal services measured on a door-to-door basis. But as shown in Figure 6.23, one study that compared the primary energy consumed by intermodal services with that of road freight services over 19 European routes found that the intermodal service saved, on average, 16% of the primary energy consumption (IRU / BGL, 2002).

The energy efficiency of intermodal services is likely to improve as a result of advances in intermodal technologies both in the transfer operation and in the utilisation of train capacity, and from increasing the density of intermodal terminals so as to minimise distances travelled.

Figure 6.23 ► Comparison of the primary energy consumption of intermodal road/rail service and road services on 19 European routes



Source: IRU / BGL, 2002.

Key point

One study found that the intermodal service saved, on average, 16% of the primary energy consumption in Europe, compared to road transport.

Policies for surface freight movement

To constrain the growth of energy use in the freight transport sector, policies and measures will be needed to improve the efficiency of freight movement, to constrain traffic growth, and to improve the efficiency of logistical systems as well as the efficiency of vehicles.

Table 6.2 shows some of the complex – and sometimes contradictory – outcomes that may result from a range of policy measures in the freight transport area.

Table 6.2 ► The impacts of policy measures on freight

Policy measure	Freight transport intensity	Modal split (road %)	Vehicle utilisation*	Energy efficiency
Higher truck taxation	↓	↓	↑	↑
Higher fuel duty	↓	↓	↑	↑
Introduction of road user charging	↓	↓	↑	↑
Deregulation of road freight sector	↑	↑	↑	↑
Liberalisation of rail freight market	↑	↓	↑	↑
Standardisation of rail equipment	↑	↓	↑	↑
Improved inter-operability of rail systems	↑	↓	↑	↑
Rail infrastructure investment	↑	↓		↑
Increased revenue support for rail track access	↑	↓		↑
Grants for rail-sidings/equipment	↑	↓		↑
Road infrastructure investment	↑	↑		↑
Improved road traffic management	↑	↑	↑	↑
Relaxation of night curfews / access restrictions	↑	↑	↑	↑
R&D support for truck design	↑	↑	↑	↑
Higher truck weight / size limits	↑	↑	↑	↑
Tighter emission controls on trucks	↓	↓		↓
Tighter emission controls on rail	↓	↑		↓
Reduction in speed limits		↓	↓	↑
Mandatory speed governors on trucks		↓	↓	↑
Improved land-use / transport planning	↓	↓		↑
Subsidised driver training schemes	↑	↑		↑
Advice / promotion on sustainable logistics	↓	↓	↑	↑
Mandatory fuel efficiency standards				↑
Benchmarking programmes			↑	↑
Accreditation schemes for trucking companies			↑	↑
Multi-stakeholder freight initiatives	↓	↓	↑	↑

*Load factor for road vehicles and rail wagons

Policies to manage total demand for truck and rail freight transport

As freight movement and economic growth are so clearly linked, reducing the volume of freight movement in a growing economy requires steps to reduce the distance that freight moves, for example by improving logistics or by altering supply chains. The European Commission has noted (EC, 2001) the desirability of decoupling transport growth from economic growth. For several years, for example, the Dutch government operated a 'transport prevention' programme that advised companies on ways of reducing their demand for freight transport by rationalising their logistics operations.

It is unlikely, however, that advice and exhortation will be sufficient on their own to effect a significant reduction in transport intensity. Given the relatively low price elasticity of demand for freight transport, it is also unlikely that price or taxation pressures will be sufficient to bring about significant change. Intervention to promote more localised sourcing, greater vertical reintegration of production and more decentralised warehousing – all of which would reduce freight movement distances – could prove counterproductive in terms of reductions in CO₂ emissions by reducing average load factors and reducing fuel efficiency.

To achieve savings in fuel use and CO₂ emissions most effectively, governments are likely to need to apply other measures.

Shifting freight from road to rail

Although rail transport is clearly more fuel efficient than road transport, and many countries' transport policies strongly favour an increase in rail freight transport, rail's share of the freight market in most countries has been contracting. This trend is likely to continue in the absence of government policy initiatives to stimulate a shift from road to rail haulage.

A recent EU study (Fiorella *et al.*, 2008), suggests that even a major increase in oil prices would be insufficient to stimulate a significant modal shift. With oil prices at USD 200/bbl, rail's share of total freight volume in the EU27 would only increase by 2%. This suggests that the cross-elasticity of demand between road and rail is relatively low.

Advances in rail technology may help to make rail more attractive. The development of new intermodal transfer systems, improvements in the interoperability of railway rolling stock and equipment between national rail systems, the application of new information technology, and more aggressive marketing by rail freight operators may all help to increase rail's share of the market. The desire of shippers to "green" their logistics operations and in particular to decarbonise the movement of freight, may also support a resurgence of rail freight over time. Further investment in rail infrastructure and intermodal systems may also help. For example, China plans a very significant expansion in its rail freight infrastructure by 2020 (Ministry of Railways, 2004).

Market liberalisation can help. One of the few exceptions to the general decline in rail freight transport has been in the United Kingdom where, partly as a result of the privatisation of rail freight and the emergence of increased competition between

the new operators, rail increased its share of the domestic surface freight market, from 8% in 1995 to 11.6% in 2006. Within the European Union more generally, rail freight market liberalisation is well underway and is likely to increase the competitiveness of rail freight services. Competition will be further enhanced by the efforts of the European Commission and individual Member States to increase interoperability across national rail networks. Improved co-ordination of these networks is critical if rail is to exploit its comparative advantage in long-haul movement. In North America, where railroad companies can provide truly continental services, rail has a much larger share of the freight market.

It is likely that a combination of fiscal, infrastructural and regulatory policies will be needed if the decline in rail's share of the freight market is to be reversed. As concern for the environment, and in particular climate change, rises, governments can be expected increasingly to promote rail freight haulage, using a mix of the following policy instruments:

- **Fiscal measures:** The nature of government financial support for rail freight operations varies widely, reflecting differences in the ownership of the service and infrastructure providers, the nature of the freight market, competition policy, and rules governing the award of state aid. Support typically comprises capital grants for rolling stock or infrastructure such as rail-sidings, discounted track access payments, operating subsidies, or reduced levels of fuel duty. Such financial support is usually conditional on the rail freight operator or the shipper demonstrating the achievement of environmental benefits from the use of rail.
- **Fiscal policy** can also favour rail by raising the cost of road transport. Current proposals to internalise the external costs of freight transport in the European Union, if fully implemented, will significantly increase the relative tax burden on road haulage. The inclusion of freight transport operations in emissions trading schemes will increase trucking costs by an even larger margin, as trucking typically produces several times as much CO₂ as rail per tkm moved.
- **The imposition of road-user charges** on trucks can also favour rail. The German government estimated that the toll system for goods vehicles (based on the distance driven) would encourage a 6% shift in long-distance freight tkms from road to rail and water (McKinnon, 2006).
- **Infrastructural measures:** Adding network capacity will benefit rail freight services particularly in those countries with congested rail systems. Some forms of investment will particularly promote an increase in freight. These include investment to install rail sidings or lengthen refuges and loops, to strengthen track to support heavier rolling stock, to expand the loading gauge, to construct freight-only lines, and to develop intermodal terminals.
- **Regulatory changes:** Deregulation, such as the abolition of common carrier obligations and tariff controls on rail freight operations, is at an advanced stage in most developed countries but progressing more slowly in some developing countries. The removal of these restrictions can allow rail to compete more effectively on a commercial basis. The deregulation of road freight operations across the developed world over the past 40 years, such as the liberalisation of freight markets in the formerly planned economies of Central and Eastern

Europe, has contributed to the modal shift from rail to road. It is unlikely that these governments will reintroduce regulation to tilt the modal split in favour of rail.

Improving road vehicle utilisation

Improving road vehicle utilisation by encouraging higher average loads per trip could provide important reductions in energy use. Governments can promote greater utilisation of vehicle capacity through measures such as road user charges, increasing the maximum loading of vehicles and improving information.

Experience in countries with truck tolling systems suggests that relating infrastructure charges to the distance travelled gives haulers an added incentive to load their vehicles more fully on both outbound and return journeys. In Switzerland, a heavy vehicle fee (HVF) scheme was introduced in 2000 to incentivise longer, better loaded journeys. Over the first three years of the HVF, the total volume of road freight movement remained stable while the distances moved by trucks declined by 8%. Roughly one-quarter of the decline in distances moved was attributed to economic factors. The remaining 6% reduction in truck distances was attributable, in part, to the introduction of higher weight limits but mostly to the HVF having encouraged improvements in logistics and particularly a reduction in empty running (Swiss Federal Office for Spatial Development, 2004).

Increasing maximum truck sizes and weights has been advocated in several countries as a cost-effective way of increasing load consolidation, and thereby achieving substantial reductions in cost, energy and emissions. Studies have been conducted in the United States (Transportation Research Board, 2002), the United Kingdom (Knight *et al.*, 2008), Germany (Umwelt Bundes Amt, 2007) and the Netherlands (Arcadis, 2006) to assess the relative costs and benefits in different national settings. These studies reach different conclusions. Government decision making on this issue has been strongly influenced by concerns about safety, public opinion and the risk of undermining the competitiveness of rail freight services.

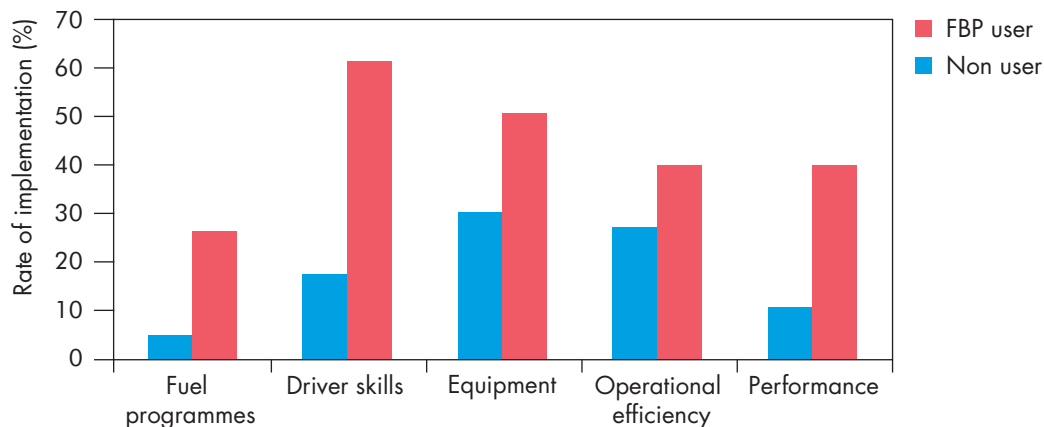
Several governments have introduced advisory, benchmarking and promotional programmes to encourage companies to improve vehicle loadings. Government agencies and their consultants work closely with industry to develop these schemes. For example:

- US EPA's SmartWay programme helps shippers to reduce their transportation footprint by applying a range of measures, some of which improve vehicle loading (EPA SmartWay, 2009). Around 1 000 shippers and carriers have now joined the SmartWay Transport Partnership through which, if they meet specified environmental criteria, they can gain accreditation. An increasing number of shippers in the United States are insisting that their carriers be SmartWay accredited.
- The United Kingdom's Freight Best Practice programme provides advice to companies through brochures, workshops and on-site advice about a broad range of measures that improve vehicle loading and fuel efficiency. Recent market research has established that companies obtaining advice from the Freight Best Practice programme showed a significantly greater propensity to implement a range of fuel savings measures (Figure 6.24). It also suggested that the Freight Best Practice programme was a very cost-effective means of promoting the

decarbonisation of freight transport operations, achieving savings at a cost to public funds of approximately GBP 8 (USD 12) per tonne of CO₂ saved.

- The Dutch Connekt programme is another government-industry partnership designed to promote sustainable logistics by minimising transport, increasing logistical efficiency and cutting the use of fossil fuels (Connekt).
- The French "Objectif CO₂: les transporteurs s'engagent" government-industry partnership voluntarily involves 23 companies that signed an agreement in which each company agrees to perform a CO₂ audit, and defined an action to reduce its environmental impact with previously defined metrics over three years.

Figure 6.24 ▶ Rates of implementation of fuel saving measures for users and non-users of advice from the UK Freight Best Practice (FBP) programme



Source: Databuild, 2007.

Key point

Companies that joined voluntary programmes improved significantly their efficiency.

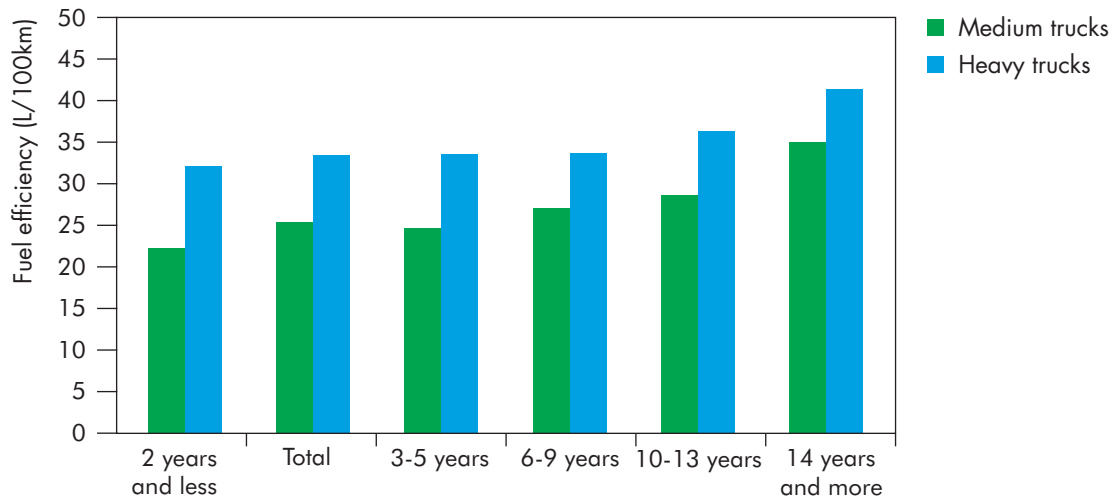
In addition, municipal authorities and other public bodies can increase load factors on vans and trucks in urban areas by supporting the development of consolidation centres and granting priority use of road space to more efficiently loaded vehicles. Examples of urban consolidation schemes exist in several European countries and in Japan (Bestufs).

Improving truck fuel efficiency

Technical measures to improve fuel economy in trucks diffuse quite slowly. Despite the conventional wisdom that commercial pressures should encourage haulage companies to respond quickly to such opportunities, participants at an IEA truck efficiency workshop (IEA, 2007a) concluded that potential fuel efficiency improvements were not being delivered as quickly or as broadly as they could have been.

Trucks have a relatively long life span. This slows the rate of technology penetration. Many of the vehicles operated in developing countries are imported when they are five to ten years old, and retired much later than in North America and Europe. Canadian data shows how the average fuel efficiency of trucks diminishes as they get older (Figure 6.25).

Figure 6.25 ▶ Decline in average fuel efficiency as truck age increases



Source: Transport Canada, 2005.

Key point

The average fuel efficiency of trucks in Canada diminishes as they get older.

Longer life spans should make it more economically attractive to retrofit fuel-saving devices to existing trucks. But road haulage industries tend to be fragmented, with much of the freight carried by small operators or owner-drivers who often lack the resources to upgrade or to retrofit new technologies. Typically, around 80% of carriers run five or fewer vehicles. Such companies generally require a short payback period on new technology, often as little as 18 to 24 months. This mainly reflects competitive conditions and low profit margins in the haulage market, concern about the effects of innovations on the resale or residual values of the vehicles, and general risk aversion. Real increases in fuel prices or the application of CO₂ pricing would shorten these payback periods for most fuel-saving technologies, but they may still not be sufficient to make long-payback technologies interesting.

Policies to increase truck efficiency

A number of governments, particularly in OECD countries, have mandated fuel economy standards as a means of improving the fleet average fuel economy of cars. A similar approach might be expected to produce similar results for freight trucks.

But the diversity of vehicle designs and functionality, together with the fragmented nature of truck manufacturing, particularly in North America, makes it more complicated to operate such a standard regime. Engines, tractor chassis and trailers are often made by different companies to specifications set out by client trucking companies. Defining standards against which to benchmark fuel efficiency is therefore extremely difficult. In comparison, the fuel efficiency of LDVs are easier to regulate because LDVs are not frequently used for towing and are rarely rebuilt in the same way as trucks. In addition, LDV consumers have volume buying power to push for specialised specifications.

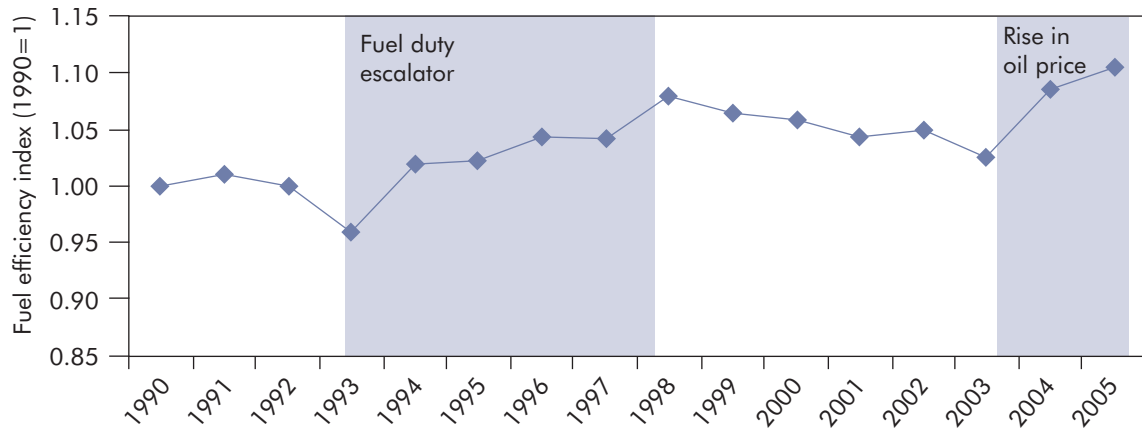
Recent steps to create such standards include:

- The Japanese government has introduced fuel economy standards for new freight trucks. Its Top Runner Program for heavy-duty vehicles (HDVs) aims to increase the fuel efficiency of new trucks by 12% between 2002 and 2015, with vehicle manufacturers' fuel consumption figures tested by means of a computer simulation model (MLIT, 2006).
- In the United States, the Energy Independence and Security Act of 2007 requires the US Department of Transportation to determine, in conjunction with US DOE and EPA, how to implement a fuel efficiency improvement programme for HDVs to include test methods, performance metrics, standards and enforcement protocols.
- The State of California passed legislation in 2006 allowing it to regulate CO₂ and other GHG emissions as pollutants - in particular in relation to GHG emissions from light- and heavy-duty vehicles. The State has specifically addressed HDV idling as a potentially important source of GHG savings and air quality improvements. A State ordinance applicable to HDVs of 6.4 t and over requires operators to shut down their engines after five minutes of idling.
- In Europe, until recently, policy measures were thought to be unlikely to provide scope for further GHG reductions in trucks beyond those already incentivised by the market, given the already high fuel costs faced by commercial transport. But during the second phase of the European Climate Change Programme, it emerged that options for further reduction may indeed exist. Since then, the European Commission has been surveying potential measures and instruments. There are no specific proposed directives or programmes at this point.

In addition to standard setting, governments can influence the fuel efficiency of trucking operations in a number of ways.

Raising fuel duties: This encourages freight operators to run their vehicles more fuel efficiently. In contrast to relatively low sensitivity of the truck/rail modal split to fuel prices, truck (technical and operational) fuel efficiency appears to be fairly sensitive, at least over the medium term. During the period of the United Kingdom government's 'fuel duty escalator' policy (1994-99), when fuel duty rose annually by 5% to 6% in real terms, the average fuel efficiency of road haulage operations rose by approximately 9% (Figure 6.26). In some countries, diesel consumed in rail freight operations is taxed at a much lower rate than that used by road vehicles; as a result, rail fuel efficiency is not subject to such strong fiscal pressure.

Figure 6.26 ▶ Effect of external factors on truck fuel efficiency in the United Kingdom, 1990-2005



Source: UK Department for Transport, 2006.

Key point

During United Kingdom 'fuel duty escalator' policy (1994-99), the average fuel efficiency of road haulage operations rose by approximately 9%.

Best practice / benchmarking programmes: The cumulative impact of small improvements has the potential to deliver significant fuel efficiency gains. Many of these would fail to be observed by the market in the absence of good information. Governments can play an important role in raising awareness of potential fuel savings and providing advice on how to achieve them. The United States SmartWay, United Kingdom Freight Best Practice, French "Objectif CO₂" and the Dutch Connex programmes all have a strong focus on fuel efficiency and provide freight operators with software tools to assess their fuel consumption and potential savings from the application of fuel economy measures. The UK has demonstrated how state-financed benchmarking schemes can be used both to measure fuel efficiency levels on a consistent basis and to give under-performing companies an incentive to raise their fuel efficiency to that of more competitive businesses.

Reducing speed limits: It has been estimated in the United States that, for heavy trucks within the range 60 mph to 65 mph, every 1 mph reduction in speed yields a fuel saving of around 0.8% (Southwest Research Institute, 2008). The mandatory installation of speed governors set at lower speed limits can significantly reduce fuel consumption. Company experience suggests that marginal reductions in the speed limit generally have little effect on operational efficiency or fleet size.

Support for R&D on engine/vehicle design: The United States government, funds fundamental research on the design and testing of more energy efficient trucks and vans. The work of the EPA on hydraulic hybrid delivery vans (EPA, 2004 and 2006) constitutes a good example of such support schemes.

Incentivising scrappage of older vehicles: Public funds can be used to incentivise freight operators to scrap older vehicles and upgrade to more fuel efficient models. The Spanish government, for instance, has recently implemented an early scrappage policy. Nevertheless, research in the United Kingdom has found that substantial public expenditure would be required to significantly reduce the average age of the truck fleet, and studies focused on LDVs have not found early scrappage programmes to be a cost-effective approach to saving fuel or cutting CO₂. This partly due to the difficult design of policies that target heavily used, high-emitting vehicles while excluding less heavily used vehicles (ECMT, 2001). This might be easier to screen in the case of commercial trucks, and is worth further investigation.

Cost effectiveness of energy reduction measures for truck and rail transport

The IEA does not yet have a well-developed set of estimates for the relative costs of the individual energy reduction measures that might be applied in the freight sector.

Table 6.3 ▶ **Trucking retrofit technology cost-effectiveness in the Canadian context**

Technology name	RMI technology cost estimates (USD per truck)	Fuel economy improvement potential (%)		Fuel savings: EEA Tech Potentials, social view - 13 years of fuel savings @ USD 0.74/L		Fuel savings: EEA tech potentials, private view - 3 years of fuel savings @ USD 1.00/L	
		RMI (%)	EEA (%)	Fuel savings, litres	Fuel savings, USD	Fuel savings, litres	Fuel savings, USD
Efficient dual tires	55	4.0	2.0	10 051	7 438	4 382	4 382
Side skirts	1 679	4.0	1.5	7 538	5 578	3 287	3 287
Gap fairing	891	2.0	0.8	3 769	2 789	1 643	1 643
Tractor aerodynamics	1 050	2.0	0.8	3 769	2 789	1 643	1 643
Base flaps	3 150	6.0	2.3	11 308	8 368	4 930	4 930
Wide base tires	5 913	5.0	2.6	13 067	9 669	5 697	5 697
APU (diesel-electric)	7 429	80.0*	80.0*	42 392	31 370	12 718	12 718
APU (battery-electric)	3 932	92.0*	92.0*	48 751	36 076	14 625	14 625
Full package of measures	16 615	22	14	70 562	52 216	25 460	25 460

* Estimates for APUs relate to fuel savings during truck idling and are not comparable to other fuel savings estimates.

Sources: EEA, 2008; RMI, 2007.

Two recent studies of heavy-duty truck fuel economy retrofit technologies have been conducted in Canada by Energy and Environmental Analysis (EEA, 2008) and the Rocky Mountain Institute (RMI, 2007). Both studies reviewed a similar set

of technologies. In the course of their study, EEA re-estimated RMI's fuel economy improvement estimates and significantly lowered some of them. EEA did not re-estimate the RMI technology cost estimates.

The principal results are shown in Table 6.3. This shows RMI's technology cost estimates, and both the RMI and EEA fuel economy potential estimates. Even using the lower EEA technology potential estimates, the results indicate that nearly all the technologies considered can easily pay for themselves within three years at a market fuel price of USD 1.00/L, reflecting the situation in Canada at the time. The study also looked at a societal cost set of assumptions, with lower fuel cost (untaxed to reflect resource costs of fuel) but more years of fuel use. The study found that all of the technologies achieve fuel savings over 13 years that are higher than their cost to purchase and install. Some, such as efficient dual tyres, save twice as much as they cost. Only wide-base tyres do not pay for themselves in three years. All these improvements, on the basis of the socioeconomic analysis, would achieve CO₂ reductions at negative cost. The implementation of a package of these measures, using wide tyres and electric auxiliary power units (APU), would result in fuel savings of 22% (RMI, 2007) or 14% (EEA, 2008). The overall fuel savings outweigh the technology costs by a factor of nearly three using EEA's estimates and societal cost analysis, meaning that the CO₂ reductions would come at a strongly negative cost per tonne.

More work is needed to estimate the costs and benefits of a wider range of technologies, as well as logistic improvements, driver training and other measures. But the results of the EEA and RMI work on retrofit technologies suggest that there are important low-cost opportunities for fuel efficiency improvement in trucking.

Looking more broadly across all types of fuel savings policies and measures for truck and rail transport, the available information permits only a very rough categorisation of fuel savings potentials and costs (Table 6.4). The measures in blue text require direct public regulatory intervention, although most of the others can also be incentivised by government fiscal policy and advisory programmes.

Measures that appear to offer the greatest potential for fuel savings at minimal cost include improved diesel powertrains, retrofit truck efficiency packages, better routing systems, lower speed limits, increased truck size/weight limits, and driver training programmes. Together, a package of measures might be able to improve overall trucking efficiency in the order of 20% to 30%, at low or possibly even negative cost per tonne CO₂ reduction. Though uncertain, this is consistent with an estimate of 33% efficiency improvement in BLUE Map at a marginal cost below USD 200 per tonne. Additional cost-effective CO₂ reductions can come from fuel switching, especially to advanced biofuels, and from modal shift. Table 6.4 represents only a starting point for further analysis, which is needed in order to fully estimate fuel savings potential and costs for each measure.

Table 6.4 ▶ A rough guide to energy savings measures for truck and rail transport

		Energy/CO ₂ savings	
		Lower	Higher
Cost per unit fuel savings/CO ₂ reduction	Lower	<ul style="list-style-type: none"> • Idling control devices • Lower RR tyres • Improved intermodal logistics through ICT • Night-time delivery • Rail locomotive efficiency 	<ul style="list-style-type: none"> • Improved diesel powertrains • Retrofit package including aerodynamics • Vehicle routing and scheduling systems • Lower speed limits • Increase truck size/weight limits • Driver training
	Higher	<ul style="list-style-type: none"> • Hybridisation of long-haul trucks • Reduce vehicle empty weight (truck or rail) • Scrappage incentives for older trucks 	<ul style="list-style-type: none"> • Hybridisation of local delivery vehicles • Advanced power trains (e.g. fuel cell) • Decentralisation of production/warehousing • Relax just-in-time regimes • More localised sourcing • Improved rail infrastructure • Fiscal incentives for use of rail • Road user charging • Biofuels, LPG, CNG

Colour code: grey = technical efficiency measures yellow = system efficiency measures green = measures directed toward rail blue = fiscal incentive measures magenta = alternative fuels.

Chapter 7 AVIATION

Key findings

- ▶ Aviation used 246 Mtoe of energy in 2006, around 11% of all transport energy used. This is expected to triple to about 750 Mtoe in 2050 in the Baseline scenario at which point aviation will account for 19% of all energy used. In the High Baseline this reaches nearly 1 000 Mtoe.
- ▶ Estimating the impact of aviation's emissions of GHGs is complicated by a number of uncertainties. Aviation emitted about 810 million tonnes of CO₂ in 2006, about 12% of all transport CO₂ emissions. But some studies suggest that aviation's overall warming impact is much higher given its emissions of other GHGs such as NO_x, CH₄ and H₂O, among others, as well as differential effects of emissions at different altitudes. More research is needed to be able to assess the full effects of aviation, taking into account all GHGs and atmospheric chemistry.
- ▶ Baseline passenger air traffic volumes grow nearly four-fold between 2005 and 2050 and air freight by a similar amount, with a five-fold increase projected in the High Baseline scenario. The reduction in the average energy intensity (energy use per passenger kilometre) of air travel worldwide of 30% in the Baseline scenario is substantial, but does not sufficiently decouple fuel demand growth from activity growth to avoid large increases in fuel use.
- ▶ The options for reducing aviation energy use below the rate of growth in the Baseline scenario may be relatively limited. There are likely to be further opportunities to improve the overall efficiency of aircraft, as well as to achieve savings through improvements in operational and air traffic control management. In the BLUE Map scenario, aircraft efficiency (including technical and operational measures) improves by 43%, cutting the growth in fuel use between 2005 and 2050 to slightly more than a doubling, rather than the tripling in the Baseline.
- ▶ A new BLUE Map/Shifts scenario includes a 25% reduction in aviation travel in 2050, cutting growth from a four-fold to a three-fold increase compared to 2005. This travel is assumed to be shifted to high-speed rail where possible, and otherwise eliminated through greater use of video conferencing and other tele-matic options. When combined with the BLUE Map efficiency improvements, energy use is reduced to a 70% increase.
- ▶ Aircraft are expected to continue to rely on liquid fuels. Low GHG biofuels appropriate for jet aircraft may become available in the next 5 to 10 years, particularly from biomass-to-liquids (BTL) processing. But the availability of feedstocks on a sustainable basis is a serious concern. In the BLUE Map scenario, biofuels use is limited to 30% of aviation fuel by 2050, or about 220 Mtoe. This accounts for about 25% of all biofuels in transport in that year.

- ▶ *The cost of specific technologies remains uncertain, but available studies indicate that substantial fuel efficiency improvements may be available at low or negative cost, taking into account fuel savings. The IEA analysis suggests that, given the high fuel use of aircraft over their lifetimes, modest improvements in efficiency in large aircraft can lead to substantial savings in fuel costs. At a low (societal) discount rate, the value of fuel savings over a 30-year aircraft life can amount to many millions of dollars, which should pay back the costs of many types of improvements. More work is needed to better estimate these trade-offs.*

Aviation trends and scenarios

Air transport has grown faster than any other transport mode in recent years and is likely to continue growing rapidly in the future. The efficiency of air transport has been improving steadily over time as airlines respond to high fuel costs, but at a much slower rate than travel growth. Thus, aircraft CO₂ emissions have been rising rapidly.

The discussion in this chapter focuses primarily on reducing CO₂ emissions. The radiative forcing (RF) effect of CO₂ from aircraft at high altitudes is estimated to be three times as high as that of CO₂ emissions at ground level (RCEP, 2007).¹ In addition, a number of other aircraft pollutants, including water in exhaust trails, nitrous oxides and sulphur emissions, may also have important GHG effects at high altitudes. The science of how these different emissions at high altitudes affect the climate is still developing. Neither they nor the potentially more significant effects of high altitude CO₂ are taken quantitatively into account in this analysis. But any steps to reduce CO₂ emissions that result in increases in the emission of other potential GHGs should be treated with caution. More needs to be done in the future to identify ways in which other pollutants can also be reduced.

Passenger travel

Commercial air travel volumes² grew rapidly between 1989 and 1999, increasing by almost 5% per year on average (ICAO, 2001). The attacks of 11 September 2001 in the United States resulted in a sharp decline in air travel for several years. The volume of international air travel did not return to its 2000 peak until 2007. However, since 2006, growth rates returned to near historical levels. Boeing projects a global average growth rate to 2028 of about 5% for passenger air traffic and 5.5% for cargo traffic (Boeing, 2009b). This would be the fastest growth rate of any transport mode. These levels of growth may be trimmed by the current economic recession, at least in the near term, although

1. See Box 7.1 for more details.

2. Throughout this chapter, passenger volumes are measured in passenger-kilometres (pkm).

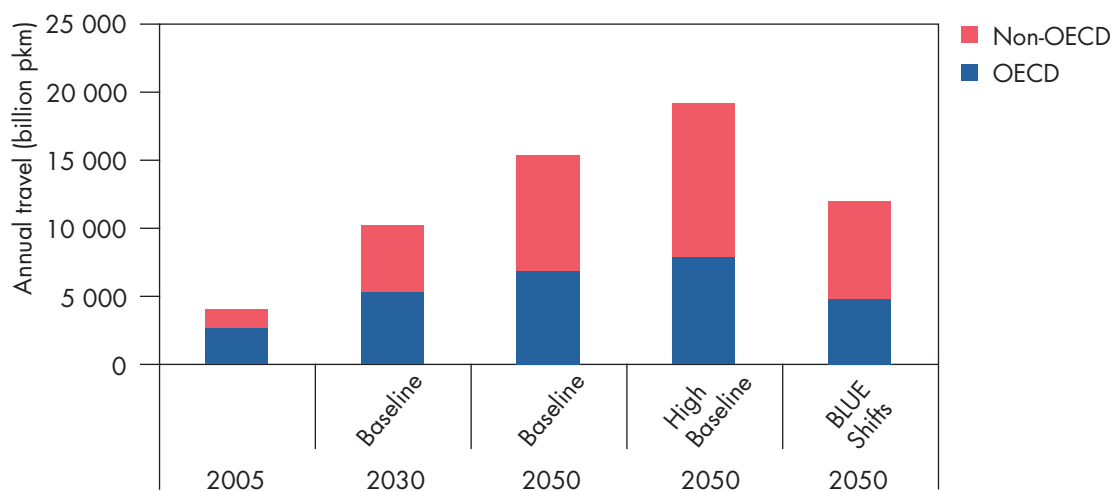
if GDP growth achieves the longer term levels projected in the IEA scenarios, the Boeing projections are reasonable.

The analysis in this chapter is based on the Energy Technology Perspectives 2008, ETP 2008 (IEA, 2008a) scenarios, recalibrated to reflect the assumptions in World Energy Outlook 2008, WEO 2008 (IEA, 2008b), with the Baseline travel projections reduced slightly. Two new scenarios, the High Baseline and BLUE Shifts scenarios discussed in Chapter 5, are also explored. The results in terms of travel volumes for each scenario are shown in Figure 7.1.

In the Baseline scenario, air travel almost quadruples between 2005 and 2050, with more than half of the growth in non-OECD countries. The worldwide average growth rate is 3.5% per year, but over 4% per year worldwide and over 5% per year in non-OECD countries until 2025. The High Baseline scenario assumes around a 0.5% higher annual rate of travel growth than the Baseline scenario, resulting in travel volumes 25% higher in 2050. This increased demand may arise from higher levels of air travel at a given income level, especially in emerging markets, than has historically been the norm in OECD countries.

The BLUE Shifts scenario assumes far lower growth in air travel than in the Baseline scenario with much of the growth shifted to high-speed rail and much of the balance displaced by aggressive efforts to promote the use of telecommunications, for example, for tele-conferencing. The result is a tripling of air travel between 2005 and 2050 in the BLUE Shifts scenario, rather than the quadrupling envisaged in the Baseline scenario. BLUE Shifts assumes strong policies to dampen air travel growth below Baseline levels, such as via major investments in high-speed rail and pricing support. However, if improvements in telecommunications prompt changes in travel patterns (e.g. with a strong trend toward video-conferencing instead of face-to-face meetings) or if fuel prices become very high, air travel growth might follow the BLUE Shifts trendline without strong interventions.

Figure 7.1 ▶ Passenger kilometres of travel by scenario and year



Key point

Air travel is set to quadruple by 2050, and will grow faster in non-OECD countries than in OECD countries.

Aircraft efficiency

Historically, the technical efficiency of aircraft has steadily and substantially improved through improvements in engine efficiencies, and aerodynamics and weight reductions, together with operational improvements such as increasing load factors, (i.e. the percentage of available seats filled on any flight), and better routing. In the United States, where the best historical data is available, the combination of technology and operational improvements has led to a total energy intensity reduction of more than 60% between 1971 and 1998, equivalent to an average annual reduction of 3.3%. Figure 7.2. shows that much of the improvement in new aircraft occurred before 1980, and that the rate of improvement has been slowing in recent years. This may suggest that some of the best efficiency opportunities have already been achieved.

Efficiencies may continue to improve as in recent years, as long as new cost-effective technical improvements are identified. But rates of improvement may start to plateau as aircraft move closer to an optimal configuration.

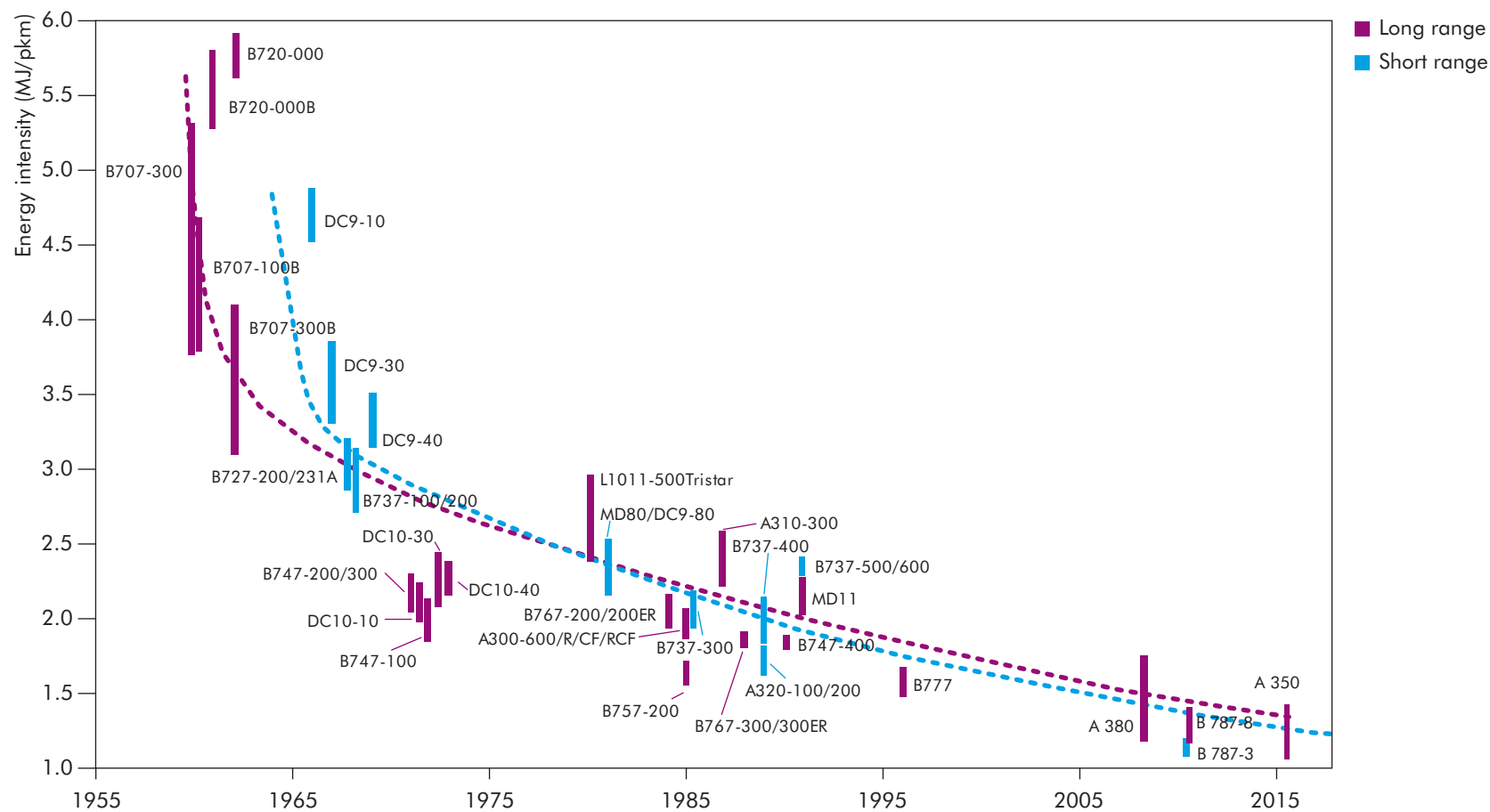
This chapter assesses likely technological developments. Based on these assessments and taking account of recent trends, the technical potential to reduce the energy intensity of new aircraft appears to be between 30% and 50% by 2050, equivalent to about 0.6% to 1.0% per year on average. This is similar to estimates made by Lee *et al.* (2001), based on the Boeing 777 introduced in 1995. Some of this potential is being deployed in the 2008-12 timeframe with the introduction of new models such as the Airbus A380 and Boeing 787. The Baseline scenario uses a near-term assumption of a 0.8% annual improvement, dropping to 0.7% after 2015.

Given the length of time it takes for new technologies to penetrate aircraft stocks, the average efficiency of the stock may lag behind new aircraft efficiency by up to 20 years. But since new aircraft are more efficient than average aircraft, the overall stock of aircraft can also be expected to improve at a steady rate, with an average annual rate that is similar to or slightly faster than the improvement rate of new aircraft.

Steps to increase operational efficiencies and load factors on the existing stock of aircraft continue to offer an important opportunity for efficiency improvement. If the annual historical rate of improvement in load factors, around 0.2% per year, continues the worldwide average load factor could reach nearly 0.8 (i.e. 80% of available seats filled with passengers) by 2025. This may be close to an upper limit.

Improving logistical operations and air traffic control, for example, by reducing delays in landing and allowing aircraft to fly on more optimal routes, may also have the potential to reduce environmental impacts by around 10% (IPCC, 1999). New practices, such as continuous descent landing patterns, can lead to additional savings. But most of these changes will require regulations to be amended and air-traffic control technologies and procedures to be increasingly harmonised (RCEP, 2007). Since most of this will require new policies and international agreements, the Baseline scenario does not include any such improvements.

Figure 7.2 ▶ Trends in transport aircraft fuel efficiency



Note: The range of points for each aircraft reflects varying configurations; connected dots show estimated trends for short-and long-range aircrafts.

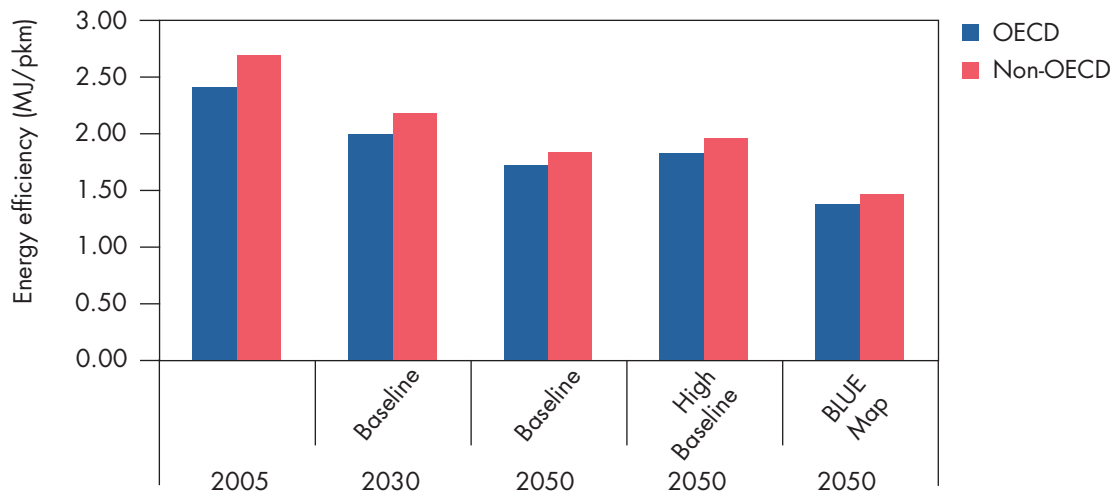
Sources: Lee, et al., 2001 IEA updates.

Key point

The next generation of planes is expected to significantly decrease energy intensity.

In the Baseline scenario, aircraft efficiency is projected to improve by 30% between 2005 and 2050, equivalent to about 1.1% per year. Efficiency improvements are slightly lower at about 0.9% per year in the High Baseline scenario. They are much higher at 1.5% per year in the BLUE Map scenario, in which an overall improvement of 43% is achieved by 2050. Since the BLUE Shifts scenario focuses on travel shifting rather than efficiency gains, it makes the same assumptions about efficiency improvements as the Baseline scenario.

Figure 7.3 ▶ Average energy intensity of aircraft by region

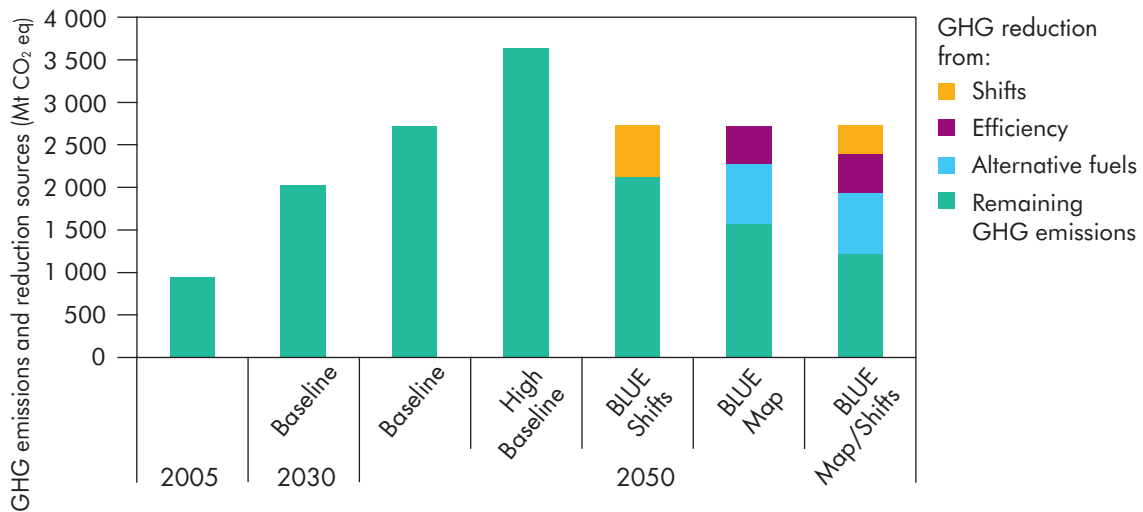


Key point

The gap between OECD and non-OECD countries is expected to remain as second-hand planes are sold mainly in non-OECD countries.

Energy use and CO₂ emissions can also be cut by using alternative fuels. The most promising alternative fuels for aviation currently appear to be advanced biofuels. These could achieve very low life-cycle GHG emissions. But a number of uncertainties surround both the cost of such fuels and the potential future volumes that can be produced sustainably. The BLUE Map scenario assumes a 30% blend of advanced biofuels, probably BTL fuels produced through biomass gasification and a Fisher-Tropsch process to produce very high quality jet fuel.

Taking into account efficiency improvements, modal shifts and biofuels, the net impacts on energy use and CO₂ emissions for each scenario are shown in Figure 7.4. This also shows the CO₂ reduction that would be projected in the Baseline scenario if the average aircraft efficiency in 2005 showed no improvement in the future.

Figure 7.4 ▶ Aircraft GHG emission projections by scenario**Key point**

Most of the reduction potential is expected to come from alternative fuels, mainly BTL.

The growth in CO₂ emissions is very large in the Baseline scenario, increasing nearly three-fold between 2005 and 2050 even after efficiency improvements are taken into account. In the High Baseline scenario, the increase is almost four-fold. In the BLUE Map scenario, CO₂ emissions in 2050 are cut by 43% relative to the Baseline scenario. With BLUE Map combined with the BLUE Shifts scenario (BLUE Map/Shifts), the reduction reaches 55%, though still above 2005 levels.

While the reductions in CO₂ included in the BLUE scenarios will be extremely challenging, the International Air Transport Association (IATA, 2009) recently made a commitment to reducing CO₂ emissions by 2050 to levels that may be similar to the BLUE Map/Shifts scenario (though not necessarily in the same manner). IATA, which represents 230 airlines comprising 93% of scheduled international air traffic, intends to use a three-step approach: (1) a 1.5% average annual improvement in fuel efficiency from 2009 to 2020; (2) carbon-neutral growth after 2020; and (3) a 50% absolute reduction in CO₂ emissions by 2050 compared to levels in 2025. This is encouraging, though it seems unlikely that such targets can be achieved without policy intervention.

An industry coalition bringing together leading international airlines, aviation sector companies and international NGO was created in 2009 to foster more ambitious GHG reduction targets. The Aviation Global Deal (AGD) Group goal is to contribute towards innovative policy solutions that incorporate international aviation CO₂ emissions into a new global climate change deal.

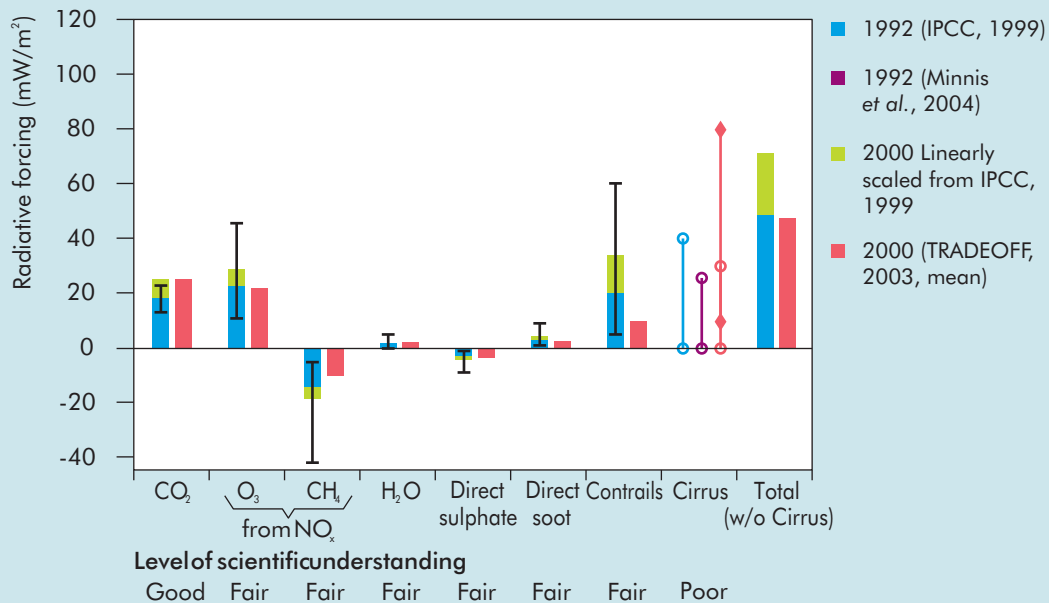
Box 7.1 ► Aviation's contribution to climate change

Aviation contributes to climate change in a number of different ways, and in more complex ways than most other sectors. The picture is further complicated by significant uncertainties about the magnitude of the climate impacts that result from various aviation emissions.

In addition to CO₂, planes emit NO_x which lead to the formation of ozone and methane (CH₄) in the atmosphere. They also emit sulphates and black carbon soot, which have RF impacts.³ Water emissions lead to contrails and the formation of cirrus clouds that also have an impact on RF. The altitude at which these emissions occur can also matter significantly.

Some measures, such as reducing overall airplane travel volumes, may reduce emissions across the board. But other measures, such as improving aircraft engine efficiencies, may result in trade-offs between different pollutants, for example achieving a reduction in CO₂ emissions at the cost of higher NO_x emissions. The levels of scientific understanding of the impacts of each of the contributors to RF from aviation varies (Figure 7.5).

Figure 7.5 ► Radiative forcing effects from various aircraft GHG emissions



Source: Sausen et al., 2005.

Notes: RF (mW/m²) from aviation for 1992 and 2000, based on IPCC (1999) and TRADEOFF (2003) results. The whiskers denote the 2/3 confidence intervals of the IPCC (1999) value. The lines with circles display different estimates for the possible range of RF from aviation-induced cirrus clouds. The overall total does not include the contribution from cirrus clouds.

Key point

A wide range of aircraft emissions may contribute to climate change, but the net effects are very uncertain.

3. RF expresses the cumulative direct and indirect impact of aviation emissions over time. RF enables an estimation of the overall contribution of aviation to climate change, as well as the assessment of the relative contribution of various emitted compounds.

The development of the best strategy to mitigate these climatic impacts requires a strong understanding both of the contribution of each source of RF, and of the trade-offs involved in trying to minimise one or another. Research is urgently needed to better understand and quantify the potential impacts of aviation emissions and the net effects of various mitigation strategies.

Aviation technologies

Aircraft fuel efficiency improvements can come from increasing engine efficiencies, lowering weight and improving lift-to-drag ratios⁴ (Karagozian *et al.*, 2006). Efficiencies in engines, aerodynamics and weight are interdependent.

The Boeing 787 incorporates a range of new technologies, for which Boeing claims a 20% fuel efficiency advantage over comparable existing aircraft. About 8% of these gains come from its engines, with the balance from aerodynamic improvements, the increased use of lighter-weight composite materials, and the use of advanced control systems (Ogando, 2007; Hawk, 2005). To justify the risks inherent in developing a new generation of aircraft, it is necessary to achieve a significant reduction (probably at least 10% to 15% in operating costs, including fuel costs) so as to make the aircraft sufficiently attractive to airlines.

Propulsion technology potential

Over the past few decades, the fuel efficiency of new jet engines has increased substantially. Engine design has focused both on improving propulsion efficiency and on increasing thermal efficiency, as well as on reducing noise levels and NO_x emissions. The need to meet stringent safety standards, as well as to reduce noise and other pollutants, often implies a trade-off with fuel efficiency. Thus, the technical challenges of making advances in all areas are substantial.

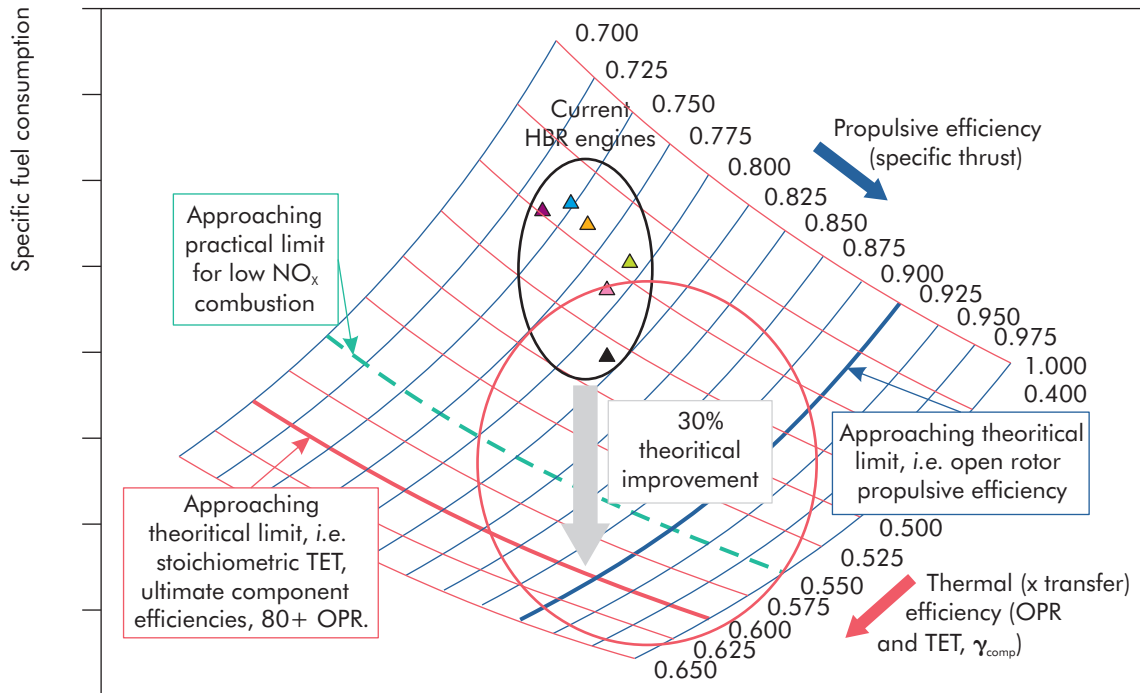
Steps to improving thermal efficiency have focused on achieving higher temperatures and pressures, with advances in compressor blade aerodynamics and new materials and coatings making important contributions. In the last 30 years, these efforts have achieved 35% reductions in fuel use, 75% reductions in noise and the virtual elimination of smoke emissions (Royal Aeronautical Society, 2005). But higher temperatures and pressures increase NO_x emissions. To counter this, engines will need to be developed with water injection systems, intercooling and chilled air coolers.

Theoretically, fuel consumption could be improved by a further 30%. But in practice it is unlikely, in the absence of new low-NO_x technologies, for engines to achieve more than an additional 20% to 25% reduction if they are in parallel to achieve expected future NO_x emissions standards (Karagozian *et al.*, 2006).

4. The relationship between the lifting force and the drag force of an aircraft.

Figure 7.6 illustrates schematically the difficulty of simultaneously shifting engines towards lower fuel burn, greater propulsion efficiency and lower NO_x emissions. A further complication comes from the need to reduce noise levels.

Figure 7.6 ▶ Fuel consumption map for jet engines



Source: Laroche, 2007.

Key point

Improving efficiencies of jet engines will become increasingly challenging when approaching theoretical limits.

Open rotor engine designs

Open rotor propulsion designs (Figure 7.7) represent the theoretical limit of propulsive efficiency and could potentially offer significant fuel savings over current engines. Open rotor engines were the subject of considerable research 20 years ago, but oil prices were insufficiently high to make them a commercial prospect. The need to tackle climate change, together with recent volatility in oil prices, have re-ignited interest in these engines, with a number of engine manufacturers seriously looking at their development and potential deployment.

Figure 7.7 ▶ Open rotor engine design

Source: Snecma, 2009.

In conventional shrouded turbofan designs, fan diameter and propulsive efficiency are limited by the drag and weight associated with the larger nacelle (housing) that is necessary for bigger fans. Open rotor designs are not limited in this way. They could potentially have a propulsive efficiency greater than 90% compared to today's turbofans, which have efficiencies of around 75% to 80%. The increased efficiency would enable reduced fuel consumption. Part of this potential could be traded for lower operating temperatures, enabling lower NO_x emissions. But the open rotor's potential fuel savings come at the cost of higher noise levels. Significant technical hurdles still remain related to vibration, certification, weight, integration with the aircraft and reliability/maintenance costs. General Electric (GE) estimates fuel consumption for the first generation of open rotor engines could be of the order of 15% less than that of a current 737 aircraft (with CFM56 engines), and that they could potentially be deployed on aircraft in 8 to 10 years time (*Aviation Week*, 2008).

Open rotor designs will need to be accepted by the market for their deployment to begin in earnest. Conventional enclosed turbofans are likely to remain preferred for long-haul flights, with light-weighting of the nacelle and reduced drag technologies used to allow increased fan size to achieve lower fuel burn. Given their slightly lower potential cruise speeds compared to conventional shrouded turbofans, open rotor engines are likely to be restricted to short- and medium-haul flights, where slightly longer flight times will be acceptable if there are operating cost savings. But these shorter flights are also those where the higher noise emissions from open rotor designs are likely to cause most problems.

Potential for improved aerodynamics

The higher the lift-to-drag ratio of an aircraft, the less energy is needed to keep it aloft. Fuel consumption varies roughly inversely with the lift-to-drag ratio at cruise speeds. Over the long term, increasing this ratio is potentially the most effective means of reducing fuel intensity. Lift-to-drag ratios can be increased with wingspan extensions and other changes to the overall aircraft design.

Retrofitting existing commercial aircraft with small additional wings (known as winglets) and with wingtip extensions has increased the lift-to-drag ratio by 4% to 7% (Greener by Design, 2005) and could yield fuel savings of 1% to 2% (Farries and Evers, 2008). The benefits of this increased lift-to-drag ratio need to be balanced against the additional weight. In the medium term, winglets and wingtip extensions can provide additional fuel efficiency gains. Adding small ribs to the wing surface to reduce the effects of turbulence can also help improve the lift-to-drag ratio and could improve fuel consumption by a further 1% to 2%.

The design of the wings on aircraft currently used for long-haul flights is optimised to minimise fuel burn at cruising speeds. This entails a trade-off between wing-span and wing weight. The fuel efficiency benefits of increasing current wing-spans would be offset by the fuel needed to carry the weight of the required additional strengthening of the plane's inboard wing area. To get round this, design cruise speeds could be reduced to allow a reduced sweep of the wing. Alternatively, advanced composite wing skins could be used to reduce weight and allow an increased wingspan.

Reduction in aerodynamic drag

Aircraft experience substantial aerodynamic drag, with associated losses in efficiency. In current aircraft designs, most of the surface area of the plane provides little or no lift and mainly increases drag. Drag, and therefore fuel consumption, can be reduced by improving the way air passes over the aircraft when it is in flight, in particular by improving laminar flow.⁵

Natural laminar flow is achieved passively by ensuring that wings are designed to achieve a gently accelerating flow of air over the front half of the wing. This reduces pressure drag. But this approach is limited to small- and medium- size aircraft. Although significant potential barriers remain to its application on larger aircraft, for wings of a low sweep angle it has been shown that this approach could be applied to aircraft around the size of the current A320 (Henke *et al.*, 1996). Natural laminar flow is already designed into some applications such as the Boeing 787 engine nacelles (Vijgen, 2008). Typically, the application of laminar flow designs to engine nacelles alone might yield 1% fuel savings.

The principles of hybrid laminar flow control are similar to those of natural laminar flow, but changes to the wing shape are complemented by measures, such as boundary layer suction, which cuts the friction associated with a thin boundary layer of air over the front half of the wing. This enables laminar flow to be maintained more effectively for larger aircraft. Applying hybrid laminar flow control processes to fins, tail-planes and nacelles (as well as to wings) has shown the potential to reduce fuel consumption by up to 15% in medium-range aircraft. More modest applications of this technology, at lower cost, are likely to be more typical initially, with a 2% to 5% improvement in efficiency (Greener by Design, 2005). The system would entail increased manufacturing and operational costs, and it would be necessary for aircraft to carry extra fuel reserves in case the suction system failed.

5. Laminar flow is the non-turbulent flow of air in parallel layers over a surface. When laminar flow is disrupted, such that different layers of air mix, eddy patterns occur that cause drag and efficiency loss.

One option to reduce technology risks might be to roll out the system initially only for tail surfaces and nacelles.

Flying wing and blended wing-body configurations

Flying wing aircraft are designed in such a way that the entire aeroplane generates lift and is streamlined to minimise drag in order to produce a high lift-to-drag ratio. The concept is not new, with significant research and actual experience with production and operation of flying wing aircraft in military applications, notably the United States Northrop Grumman B-2 Spirit. The blended wing body (BWB) is a cross between a flying wing aircraft and a conventional aeroplane (Figure 7.8). The higher lift-to-drag ratio of BWB aircraft is achieved as a result of the reduced need for tail/fin surfaces, a more structurally efficient design and higher cruise altitudes.

With flying wing concepts, it may be possible to cut the fuel use of new aircraft very significantly compared to the average new planes of today. Studies conducted by Boeing show fuel reductions of approximately 20% to 25% compared to currently sold aircraft (Barr, 2006; Farries and Evers, 2008). The development of flying wing aircraft will require significant technological and operational breakthroughs but commercialisation by 2025 is possible (Leifsson and Mason, 2004).

Figure 7.8 ▶ Blended wing body – SAX-40 design



Source: Cambridge-MIT Institute, 2006.

BWB aircraft are likely to face some consumer resistance, at least initially, as the number of windows will be limited and passengers seated further from the centreline will experience greater vertical movement when the aircraft turns. The wingspan of such planes will also be wider than current aircraft, potentially creating infrastructure difficulties at airports. Early applications are therefore likely to be in military transport or tanker aircraft, and in commercial freight operations.

A longer-term option is a BWB aircraft with hybrid laminar flow. Each of the individual technologies would have to be developed in parallel in order to prove the technologies and reduce their costs. The time required to reach a viable commercial aircraft design of this kind has been estimated at 20 to 25 years. Potential fuel savings could be substantial. Although dependent on specific design features, improvements of up to 40% compared to current long-range, swept wing aircraft have been estimated (Greener by Design, 2005).

Materials-related technology potential

Lightweighting aircraft by using new materials and composites can also significantly improve fuel efficiency. Much of the current effort of aeroplane manufacturers and component suppliers to reduce fuel consumption and GHG emissions is concentrated in this area.

Carbon-fibre reinforced plastic (CFRP) is stronger and stiffer than metals such as aluminium, titanium or steel, but its relative weight per volume is half that of aluminium and one-fifth of that of steel. In addition, CFRP is very corrosion-resistant and is considerably more fatigue-resistant when it is produced under ideal manufacturing conditions. One of the main challenges is to develop ways of assuring such conditions.

CFRP has been increasingly used in aircraft frame construction. About 50% of the weight of the body of a Boeing 787 is made up of CFRP and this contributes around one-third of the aircraft's 20% fuel efficiency advantage over comparable existing aircraft. In the near and medium term, the use of this material in wings, wing boxes and fuselages will increase as the technology matures. Full replacement of aluminium by CFRP could provide a 10% weight reduction in medium-range aircraft, and 15% in long-range aircraft (M&C, 2007).

Fibre metal laminate (FML) consists of a central layer of fibre sandwiched between one or more thick layers of high quality aluminium. It is used for about 3% of the recent Airbus A380 fuselage skin, the first time it has been used in civil aircraft. FML has also been developed for aircraft wing applications. It is stronger than CFRP and will allow a further 20% weight reduction compared to CFRP constructions (M&C, 2007).

Engines can be lightweighted by using composite materials with high-temperature tolerances. This not only reduces weight but also allows higher operating temperatures and greater combustion efficiency, both of which lead to reduced fuel consumption. Several promising lightweight, high-temperature composites are under investigation for aviation engine applications (Hoeveler, 2004). But the benefits of reducing engine weight on fuel consumption, all other things being equal, are relatively small. For example, for a 15 000 km range aircraft, a 10% reduction in engine weight would reduce fuel consumption by a little more than 1%.

Combining the technical efficiency options for airframe improvements and weight reduction to improve the lift-to-drag ratio shows a potential net improvement of around 20% to 30% after allowing for interactions. Most of these savings will come from lightweighting and from laminar or hybrid laminar flow wings. This does not assume any shift away from current aircraft designs to newer designs such as flying wings. If such fundamental design changes were also undertaken, an additional 10% to 15% improvement might be achievable by 2050 across the fleet.

Operational and air traffic management system improvement potential

Aircraft movements on the ground and in flight can have an important impact on fuel use. From start-up through to taxi and take-off, to cruise, to approach for landing and taxiing on arrival, operations must balance traffic congestion, safety and fuel burn issues. Current operational practices are not always optimal from a fuel burn perspective. New technologies, as well as changes in operational procedures, could play a role in reducing fuel burn.

Air traffic management systems

The current global air traffic management (ATM) system pays little regard to fuel use. It has been estimated that current ATM systems and practices in Europe mean that, while still maintaining essential safety margins, fuel burn is 7% to 12% higher than necessary (EC, 2008).

A number of current practices reduce the fuel efficiency of ATM and operations. Longer routes are flown more than necessary due to airspace fragmentation. Traffic management at airports is usually on a first-come, first-served basis, while aircraft have designated slot times on the runway for take-off. The lack of a coherent approach to the management of airspace and airport operations, as well as ATM systems that are not optimised to minimise fuel burn, mean that there are significant additional CO₂ and noise emissions, for example as aircraft queue to take off, than the theoretical minimum. Table 7.1 gives estimates for a typical 99-minute flight in the European Union, showing potential savings of 8 to 14 minutes and a reduction in fuel use of 7% to 11%.

Table 7.1 ► Potential savings in time and fuel from improved ATM and airport operations

	Time (min)	Fuel (kg)	Fuel as % of average flight
Shorter routes	4	150	3.7%
Improved flight profile	0.0	23	0.6%
Better approach procedures	2 - 5	100-250	2.5-6%
Improved aerodrome operations	1 - 3	13 - 40	0.3-0.9%
Total savings per flight	8 - 14	300 - 500	7-11%
Average intra-EU flight	99	4 300	100%

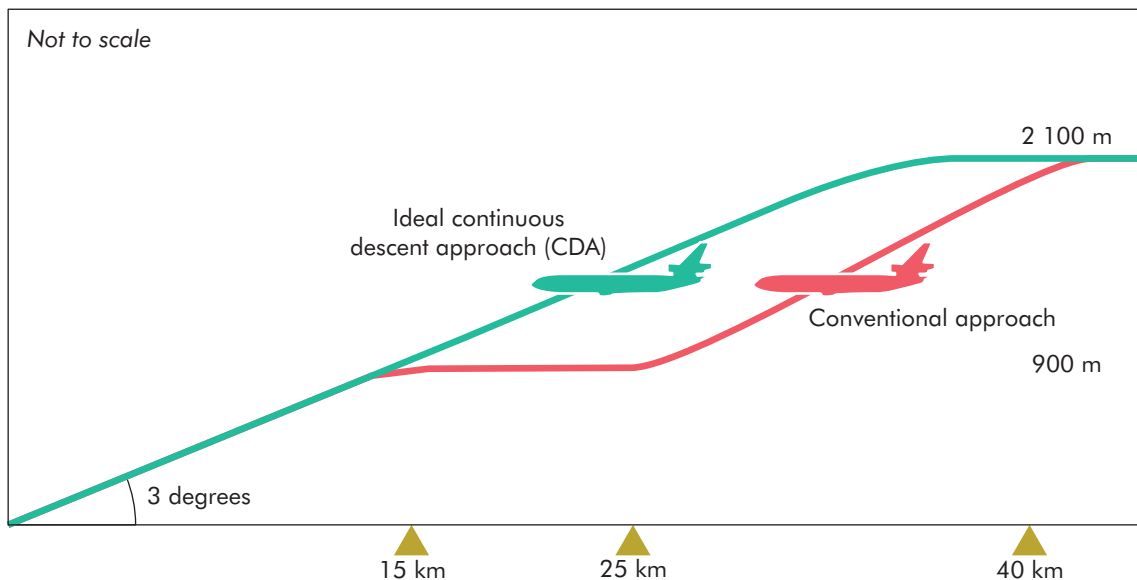
Source: Eurocontrol 2008.

The International Civil Aviation Organisation (ICAO) estimates that fuel savings of about 5% could be expected by 2015 in the United States and Europe as a result of specific, planned changes to air traffic management systems. It is uncertain whether those envisioned changes will occur within that time frame. In the longer term, somewhat larger savings are projected (ICAO, 2004).

Continuous descent approach (CDA)

The positioning of an aircraft on its final approach influences its fuel consumption as well as noise. Generally, aircraft are cleared to descend to successively lower altitudes with periods of horizontal flight between descents. These changes in descent angle and approach result in higher noise and fuel consumption than would a continuous descent from cruise altitude with some final adjustments to remain on the glide slope for landing (Figure 7.9).

Figure 7.9 ▶ Ideal continuous descent trajectory



Source: ERCD, 2007.

Key point

Continuous descent can significantly cut landing-related fuel use.

Modern electronic ATM and airplane systems have made CDA a viable alternative to conventional approach paths, although airspace constraints or safety issues may limit its universal application. CDA has already been applied at some airports. Analysis has shown that CDA could save between 5% and 11% of the fuel used in a Boeing 767 or 757 aircraft in its last 300 km to landing. This as a share of total fuel savings depends on the total journey length.

Current ATM improvement programmes

A number of OECD member countries have programmes to promote more efficient ATM systems. In the European Union, an ATM R&D programme is in its development and demonstration phase with a budget of EUR 300 million through to 2013. After this, industry is expected to lead deployment until 2020. The goal of this programme is to reduce fuel inefficiency (losses due to ATM) from an estimated current level of 12% to 9%, while accommodating approximately 60% more air traffic (EC, 2008).

In the United States, the Federal Aviation Authority's NextGen ATM system, although primarily designed to reduce congestion issues and meet traffic growth, also aims to move away from current ground-based technologies to a new and more dynamic satellite-based technology called ADS-B. All aircraft will be required to be fitted with the system which will use GPS, coupled with data management and communication systems, to allow the seamless use of the aircraft and other system data by air traffic control and pilots. An improved and integrated weather information system, trajectory-based routing and improved management and procedures also aim to reduce delays and fuel use. The modelling assumptions predict a goal of 3% fuel savings in 2015 and between 6% and 10% savings by 2025 (Farries and Evers, 2008).

Overall, the global inefficiency in the existing ATM system is probably of the order of 10% to 15%. Around 5% to 6% is likely to be addressed by current plans for ATM improvements. An additional 5% saving appears to be a reasonable global potential to be unlocked by policy changes.

Operational changes to reduce fuel consumption

Operational procedures at airports and in flight can have a significant impact on fuel consumption. Many of the possible options to reduce fuel consumption would require a radical change in current aviation practises and some would require changes to aircraft. These factors are likely to significantly constrain their adoption.

Options include:

More non-stop routes: The hub-and-spoke system common for most airlines, in which flights for an airline are routed through a large "hub" and onward flights to different destinations taken from this hub, is inherently inefficient from a fuel-use perspective. Ensuring more direct connections would help reduce fuel use. But hub-and-spoke systems appear to be more cost effective for many airlines. They may also result in higher overall load factors, thereby improving efficiency.

Multi-stage, long-distance travel: For a given standard of technology, there is a travel range that maximises payload fuel efficiency. This reflects the trade-off between the energy lost during take-off/landing cycles and the energy lost by carrying larger fuel weights over longer distances. With today's standard of technology and the most fuel-efficient aircraft, the optimal flying range is approximately 4 000 km. This is considerably less than typical current flying ranges. Studies suggest that a substantial reduction in the fuel used on long-range travel could be achieved by limiting stage lengths to 7 500 km or less. For example, compared to a single 15 000-km flight, three 5 000-km staged flights could reduce fuel use by around 17% (Green, 2006). A redesign of the aircraft to limit maximum range would extend these savings to 29%. Based on the flight patterns for a single day in 2002, this approach might save 7% of all aircraft fuel consumption (Farries and Evers, 2008). Such changes would, however, necessitate many more stopovers for long-range travel, which would lengthen travel times and may prove unacceptable to many travellers. Additional landings and take-offs might also reduce the savings potential somewhat as intermediate airports may not always be on the shortest routes.

High-speed towing: Aircraft could be towed from gates to the runway threshold for take-off and from the runway to the gate after landing. Savings would be modest, perhaps 1% to 2% of fuel burn and there are some design implications for aircraft.

A number of other options have been considered, such as assisted take-off similar to systems used on aircraft carriers, formation flying, and in-flight refuelling. But none of these appears viable from a practical or economic perspective.

Some options are already being taken up, such as more efficient ground routing and parking of aircraft at airports. Airports Council International recently began a certification programme for airports whereby they can achieve an Airport Carbon Accredited (ACA) label by undertaking a series of specified measures to cut airport emissions (WSP, 2009). These include aircraft landing / take-off cycle emissions; surface access to the airport for passengers and staff; and staff business travel emissions. The net effects of full compliance will be measured as airports achieve this in coming years.

Summary of technology potential

Estimating the overall savings from integrating different technologies requires a number of assumptions to be made that can only be validated after the technologies are deployed. Table 7.2 seeks to estimate the contributions that might be available from specific engine and airframe technology developments, as well as the benefits that might accrue from ATM and operational improvements, approximately in the 2030 time frame. The total takes into account the fact that the individual savings are not additive and that some interactions would reduce the overall potentials, based on various estimates in the literature.

Table 7.2 ▶ **Future aircraft fuel intensity reduction potential compared to today's aircraft**

Type of improvement	Percentage fuel intensity reduction
Airframe aerodynamics	20-30%
Airframe light-weighting	20-30%
Engine technologies	15-25%
ATM and operations	7-12%
Total	40-50%

Note: The total accounts for non-additive effects of combining measures.

Other environmental impacts of efficiency measures

Changing aircraft technologies and aviation operations to reduce fuel use and CO₂ emissions can also have a range of unintended impacts, for example in terms of local air pollutants, some of which are also GHGs, and noise. Table 7.3 provides

an overview of some of the co-benefits and potential negative impacts of various measures, including the impacts on fuel efficiency of measures primarily intended to reduce noise (such as nacelle modifications and steep climbs after take-off) and/or to reduce pollutant emissions (such as reduced thrust during take-off).

Many measures have conflicting impacts. Only CDA benefits all three environmental aspects (noise, local air quality and climate). In all other cases, trade-offs are necessary. While some operational measures may have conflicting impacts, a general reduction in the volume of air travel is likely to provide benefits in all environmental areas. Lightweighting also provides benefits across all areas, as do most types of aerodynamic improvement.⁶

Table 7.3 ▶ Trade-offs between noise, local air quality and climate from various measures

	Noise	Local air quality	Climate
Nacelle modifications	• Reduced noise	• Increased HC & CO	• More fuel burn/CO ₂
Increased engine pressure ratio & temp		• Increased NO _x • Reduced HC & CO	• Reduced fuel burn/CO ₂
Reduce cruise altitude			• Increased fuel burn/CO ₂ • Increased NO _x • Less increase in ozone • Reduced contrails
Increase engine bypass ratio	• Reduced noise	• Increased NO _x	• Reduced fuel burn/CO ₂
New runways	• New noise exposures	• Reduced delay (fuel burn)	
Reduce polar flights	• Potentially increased noise exposures		• Less effects on stratosphere • More fuel burn/CO ₂
Steep climb	• Reduced noise	• More fuel burn	• More fuel burn/CO ₂
Continuous descent approach (CDA)	• Reduced noise	• Reduced delay (fuel burn)	• Reduced fuel burn/CO ₂
Reduced thrust takeoffs	• Reduced noise	• Reduced NO _x • Reduced PM • Increased SO _x	• More fuel burn/CO ₂

- Positive effects
- Negative effects
- Mixed effects

Aircraft alternative fuels

Aviation fuels need to deliver a large amount of energy per unit of mass and volume in order to minimise the weight of fuel carried for a given range, the size of fuel reservoirs, and the drag related to on-board fuel storage. They also need to be thermally stable, to avoid freezing or gelling at low temperatures, and to satisfy

6. Some, such as nacelle modifications, may require trade-offs between efficiency and noise levels.

other requirements in terms of viscosity, surface tension, ignition properties and compatibility with the materials typically used in aviation.

A number of potential alternative aviation fuels exist. Not all of them, however, would significantly reduce GHG emissions. The most likely alternative fuels for aviation are synthetic jet fuels, since they have similar characteristics to conventional jet fuel. These can be derived from coal, natural gas or biomass. Liquid hydrogen may offer an additional option in the longer term, as it delivers a large amount of energy per unit of mass, although not per unit of volume. Other options, such as methane, methanol and ethanol, are characterised by unacceptably low energy density and energy per unit mass, and are not therefore likely to be used in aviation. Fuels are covered in Chapter 2, but a summary of their applications for aircraft are provided here.

Biodiesel

Biodiesel-like fuels derived from vegetable oils are not generally suitable without further processing for commercial aviation applications as they freeze at normal aircraft cruising temperatures. They are also not thermally stable at high temperatures in the engine. But they can be hydro-treated, which converts them to a fuel that is much closer in properties to conventional jet fuel and overcomes these problems. The resulting fuel is increasingly known as hydro-treated renewable jet fuel or HRJ fuel (ICAO, 2009). Hydro-treating can be carried out at refineries, but it adds an additional cost to the basic cost of production. It also suffers from the drawbacks of any fuel derived from vegetable oils, such as concerns regarding the availability of feedstocks and possible competition with other feedstock uses such as food and livestock feed.

Fischer-Tropsch (FT) fuels from fossil feedstocks

Synthetic fuels are high quality fuels that can be derived from natural gas, coal or biomass. These fuels are typically created by gasification to form a synthesis gas, mainly comprised of CO₂ and hydrogen, followed by conversion to liquid hydrocarbon fuels in the FT process. The FT process is technically mature. Synthetic jet fuels from coal, natural gas or other hydrocarbon feedstock are chemically similar to conventional kerosene jet fuels and ideally suited to supplement or replace them. They have high energy density and exhibit excellent low-temperature and thermal stability. They can even provide an efficiency increase compared to conventional jet fuel (Karagozian *et al.*, 2006). Coal-derived synthetic aviation fuels have already been certified in South Africa, where the certification of blends is also progressing.

But such fuels suffer from being expensive to produce and from the large volumes of CO₂ they emit during the manufacturing process. If synthetic fuels are to contribute to GHG emission reductions, CO₂ from the manufacturing process must be captured and stored. Even with CO₂ capture, however, these fuels will only achieve life-cycle CO₂ emissions that are comparable to conventional petroleum-based jet fuel.

Given the likely cost reductions for the large-scale production of synthetic fuels from natural gas and coal, and expected rising prices for conventional oil and oil products such as jet fuel, the Baseline scenario assumes substantial increases in the use of synthetic fuel in jet fuel. This reaches 25% of aircraft fuel use by 2050. But since these are very high CO₂ fuels, they are eliminated in the BLUE Map scenarios, aided by efficiency gains and lower demand for fuel.

Fischer-Tropsch (FT) biomass-to-liquid (BTL) fuels

BTL processes using FT technologies are likely to be deployed within the next five to ten years, subject to the resolution of a number of technical obstacles. If deployed, these fuels may offer an important GHG reduction opportunity for aircraft, since the combustion characteristics of BTL fuels are very similar to those of conventional jet fuels. In addition, BTL fuels can provide much larger benefits in terms of energy consumption and reductions in GHG emissions on a life-cycle basis than can fossil FT synthetic jet fuels. Some analyses suggest that BTL fuels as a replacement for diesel fuel can achieve GHG savings of over 80% on a life-cycle basis (Wang, Wu and Huo, 2007).

The principal drawback of BTL fuels is their production cost per unit of energy delivered. BTL plants need to be very large to be cost-competitive. But large production facilities are incompatible with the dispersed nature of the required biomass feedstock and the high cost of its collection. Since fuel costs are a significant share of total costs in the airline industry, high cost BTL fuel would be unlikely to be adopted without policies that require their use or that make them price competitive with conventional jet fuel.

Liquid hydrogen

Hydrogen is a potential fuel for aircraft, but its use poses a number of significant challenges. It would be most likely to be stored on board as a cryogenic liquid (LH₂) to minimise volume. A number of significant modifications would be required to both engine systems and airframe designs to accommodate liquid cryogenic fuels.

Insulation and pressurisation requirements make it impossible to store LH₂ in aeroplane wings, as is done with kerosene jet fuels. In addition, though LH₂ has a very high energy density per unit of mass, its energy density, even in liquid form, is only one-quarter by volume that of current jet fuel. The storage tanks needed for large volumes of cryogenically cooled hydrogen would increase the weight of large commercial aircraft by over 10% (Daggett *et al.*, 2006). Modifications would also be necessary to the fuel management system and temperature controls.

The use of LH₂ would require a completely different aircraft design, and would pose significant challenges for engines. It would also require substantial modifications to airport infrastructures, including a completely different fuel distribution infrastructure. Overall, LH₂ is not promising as an alternative fuel for aviation in the near or medium term. It could only be viable in the long term if there were significant technological developments, entirely new aircraft designs and substantial infrastructural change.

Fuels summary

Overall, BTL fuels appear to offer the best medium-term and possibly long-term potential for technically acceptable, very low life-cycle CO₂ emission aircraft fuels. Only small amounts of biofuels are assumed to be used in the Baseline scenario. In the BLUE Map scenario, BTL fuel reaches 30% of aircraft fuel use by 2050, with the remainder being conventional jet fuel. Much higher levels of BTL fuel use are certainly possible. As outlined in Chapter 2, the limit of BTL use is linked to environmental and land-use controls placed on the use of biofuels in the BLUE scenarios, not because of a technical limitation to the use of BTL in aircraft.

Aircraft efficiency improvement costs and benefits

Although planes have a service life of 30 or more years, buying more fuel efficient planes can provide net economic benefits after just a few years of operation. This section explores the potential costs and fuel savings from aircraft efficiency improvements. It also looks at the potential costs and savings that would arise from retiring aircraft early so as to secure technology improvements. The costs of specific technologies are also reviewed, although given the lack of publicly available information it is not possible to include a full analysis. Improving available information on the costs of various types of aircraft efficiency and operational improvements is a critical area for future research.

Costs and benefits of aircraft improvements

Long-haul planes fly on average about 2 million km per year, and short-haul planes about 1.5 million km per year (IATA, 2008). Taking two recent examples of product upgrades from Boeing,⁷ Table 7.4 shows the potential gain in terms of fuel efficiency and cost savings that would result from flying the newer, more efficient model on long-haul routes with an oil price of USD 120/bbl, equivalent to around USD 0.90/L of jet fuel (untaxed). About USD 6 million to USD 8 million could be saved every year by flying the more recent model. Using a 10% discount rate over 30 years of fuel savings, this amounts to a net present value of savings in the range of about USD 60 to 80 million, equivalent to about 10 years of undiscounted fuel savings. The saving more than doubles if a 3% (societal) discount rate is used.

Given purchase price differences of USD 40 million for the B787 compared to the B757, and around USD 50 million for the 747-800 as compared to the 747-400,⁸ the fuel savings over 30 years more than pay for the additional price of the newer, more efficient aircraft using a 10% discount rate assumption. With a 3% discount rate (more consistent with concerns for the future climate), the savings are far greater than the incremental cost of the more expensive plane in both cases. In these circumstances, any consequential reductions in CO₂ are achieved as a cost-free co-benefit.

7. These two examples were chosen since they appear to be the two best “matched pairs” available for comparison purposes. The Airbus A380 will also provide substantial fuel savings per seat-km compared to earlier aircraft, but there is no directly comparable aircraft.

8. Each aircraft is available in a range of configurations, with significant variations in prices; these estimates are meant to give an indicative price, based on available information.

Table 7.4 ▶ Fuel savings and costs from new generation planes

	B767	B787	B747-400	B747-800
Seat capacity	250	250	460	467
Load factor	80	80	80	80
Energy intensity (MJ/seat-km)	1.9	1.3	1.8	1.4
Fuel use (L per plane km)	10.8	7.4	18.6	14.7
Annual plane-kilometres of travel (million)	2.0	2.0	2.0	2.0
Annual fuel consumption (million L)	22	15	38	30
Annual savings (USD million @ USD 120/bbl or about USD 0.90/L)	6.4		8.6	
Savings over 30 years, 10% discount rate, (USD millions)	60		81	
Savings over 30 years, 3% discount rate, (USD millions)	125		169	
Approximate aircraft purchase costs (USD millions)	150	190	230	280
Purchase cost difference (USD millions)	40.0		50.0	

Sources: IEA estimates based on aircraft data from Boeing's website (Boeing, 2009) and previous reports. Airplane cost data from Air Guide Online, 2009.

Many new aircraft being purchased today are the most efficient available, so most of these benefits already accrue in the Baseline scenario. Beyond this, the main options for securing faster or additional efficiency improvements lie in further fuel efficiency features (possibly added at a faster rate to each new aircraft model introduction) or in the earlier retirement of older, less efficient aircraft.

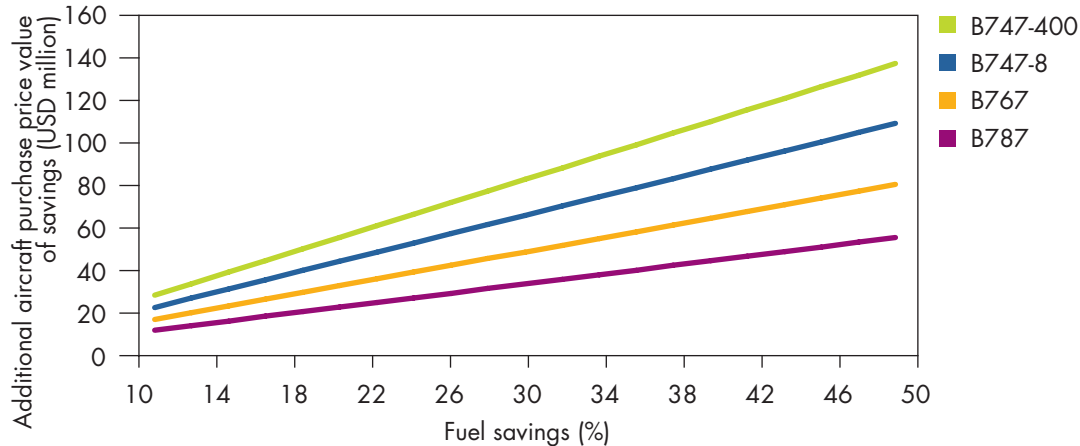
Increasing the efficiency of new aircraft in the future

7

Figure 7.10 shows the additional aircraft purchase prices for a range of aircraft types that would be justified by the fuel savings they would generate at different oil prices (assuming, as in Table 7.4, a 10% discount rate over 30 years of plane life with oil at USD 100/bbl). It is axiomatic that the more efficient a plane becomes, the less value there is in additional percentage reductions in fuel savings. So a 15% fuel efficiency improvement on a 787 is worth less than the same percentage improvement on a 767. On this basis, investments in the next generation of planes will be more difficult to justify commercially on fuel savings alone, as the fuel savings will be lower.

The incentive to invest in new aircraft, rather than to invest in efficiency improvements in the existing fleet, is also reduced in respect of larger aircraft, such as the 747 or the A380, which use large amounts of fuel. A relatively small, percentage efficiency improvement has the potential to generate significant savings in these circumstances. This has implications for technology deployment, as it may be possible to roll out technologies with high initial costs more cost-effectively on larger, long-range aircraft, before such technologies are diffused to smaller, long-haul and short-haul aircraft after operational knowledge is gained and costs come down.

Figure 7.10 ▶ Value of fuel savings from efficiency improvements, starting from existing aircraft



Note: Data is based on Table 7.4, using 10% discount rate and USD 100/bbl oil price.

Key point

Flying the latest fuel-efficient planes is cost effective as fuel savings quickly exceed the additional capital expense of new aircrafts.

The successful deployment of new technologies to deliver fuel efficiencies will depend, amongst other things, on the cost of those technologies relative to the efficiencies they are expected to deliver. There is very little recent research on this question.

Lutsey (2008) provides a recent, fairly comprehensive review of aircraft efficiency studies, although all the reviewed studies are from the 1990s. Table 7.5 shows for these studies the estimated potential fuel efficiency improvements and the estimated cost-effectiveness per tonne of CO₂ reduced.

Table 7.5 ▶ Aircraft fuel and CO₂ reduction cost estimates

Source	Energy intensity		Energy intensity change from Baseline (%)	Initial cost (no fuel savings) (USD2008/t CO ₂)	Lifetime cost effectiveness (30 years, 7% discount rate, USD2008/t CO ₂)
	(L / available seat-km)	L / km			
NRC, 1992	0.022	3.8	-36%	49	-11
IPCC, 1999	0.028	4.8	-20%	46	-20
ETSU, 1994 (low)	0.018	3.1	-48%	57	0
ETSU, 1994 (high)	0.013	2.3	-62%	70	17
CAEP, 1995	0.026	4.5	-25%	46	-18
DCAD, 1997	0.028	4.8	-21%	46	-20
Average	0.023	3.9	-35%	52	-9

Source: Lutsey, 2008.

The results suggest that very high efficiencies can be achieved at low or negative cost per tonne of CO₂ saved for packages of aircraft improvements. The efficiency potentials shown in the table are close to, or even better than, the 787, with negative costs taking into account fuel use with a 7% discount rate over the 30-year life of an aircraft. At a 3% discount rate, the net CO₂ costs would be even lower.

Only one recent study has been identified that provides specific cost estimates for technology improvements in future aircraft (OMEGA, 2009). The paper develops cost curves for technologies, as well as operational changes in the context of the United Kingdom and the European Union for current and future scenarios. The paper cautions that the analysis needs further development and verification. But it suggests that many low-cost options are likely to be available, particularly in the medium term. For example, for the European Union in 2025, assuming an oil price of USD 75/bbl, the paper estimates that of the order of 30% improvements in aircraft and system efficiency could be achieved at negative or very low cost per tonne CO₂ saved.

Overall, although much more work is needed in this area, the OMEGA study suggests that there could be a large potential for reducing CO₂ from aircraft through technology improvements and other measures at very low or negative cost per tonne of CO₂ saved.

Accelerating fleet turnover

Replacing planes with more modern versions before the end of their life spans can provide significant fuel savings, although it is a relatively expensive option and the benefits will tend to decline as planes are brought out of service increasingly early.

Table 7.6 illustrates the possible trade-offs involved in early plane retirement. This example examines over a 60-year period (1990-2050) the impact of planes being retired every 30 years (*i.e.* two planes spanning 60 years) and retired every 20 years (*i.e.* three planes spanning the period). GHG emissions from plane production are not taken into account, but have been separately estimated to be very low compared to the GHG emissions due to flights (IEA estimates). The analysis assumes oil at USD 100/bbl over the entire time frame, aircraft costs rising by about 2% in real terms every five years reflecting efficiency improvements, and that the planes are involved in long-haul travel of 2 million km per year. Future costs are not discounted.

On this basis, it is much more expensive to retire planes early than to run them for their full service lives. The cost per tonne of CO₂ saved in this early retirement example is several hundred USD. Although there may be scenarios in which early retirement is cost-effective, modest changes to the assumptions used here do not alter the results significantly.

Table 7.6 ▶ Fleet renewal acceleration costs

	Case 1			Case 2				Difference
	Plane 1	Plane 2	Total	Plane 1	Plane 2	Plane 3	Total	Case 2 minus Case 1
Years of aircraft life	30	30	60	20	20	20	60	
Date of aircraft purchase	1990	2020		1990	2010	2030		
Purchase cost (USD millions)	150	169	319	150	162	176	488	169
Fuel efficiency (L/km)	15	10.3		15	11.7	9.1		
Fuel use over aircraft life (million L)	900	618	1 518	600	468	364	1 432	-86
Fuel costs over aircraft life (USD millions)	747	513	1 260	498	388	302	1,189	-71
Total purchase plus fuel costs (USD millions)	897	682	1 579	648	550	478	1,677	98
CO ₂ from fuel over aircraft life (million t)	2.3	1.5	3.8	1.5	1.2	0.9	3.6	-0.2
Resulting cost per t CO ₂ reduced (USD)								454

Summary of cost analysis

Although much additional work is needed to fully understand the potential and cost of reducing CO₂ emissions from aircraft and from the aviation sector in general, this analysis suggests that:

- The fuel savings potential from aircraft efficiency improvements can be large, and can help pay for the costs of these efficiency improvements.
- Fuel cost savings at low discount rates can be quite large and may fully justify aircraft efficiency improvements that would enable CO₂ reductions to be achieved at near-zero or even negative cost, on a societal cost basis.
- Replacing aircraft before the end of their expected life spans appears unlikely to be a cost-effective way of achieving CO₂ reductions.

Chapter 8 MARITIME TRANSPORT

Key findings

- ▶ IEA statistics indicate that maritime transport accounted for 220 Mtoe of energy use in 2006, about 9% of total transport fuel use. Approximately 83% was accounted for by international transport and the remainder by national shipping. But estimates of international maritime energy use vary widely, from 183 Mtoe to nearly 300 Mtoe in 2006. The IEA data do not include reporting from some countries, but global fuel supply-demand balances suggest that 300 Mtoe may be too high. More work is needed to develop data sets that help resolve these differences.
- ▶ International shipping relies mainly on heavy fuel oil (HFO), a high-sulphur, low-cost fuel. Shifting to alternative fuels may be relatively expensive for ships. The high sulphur levels in HFO mean that the total GHG impacts of shipping are likely to be low or even negative, since sulphate emissions have a negative radiative forcing (RF) effect. This will probably change as ship fuels increasingly become desulphurised in coming years. Sulphates have other negative impacts on the environment such as acid rains.
- ▶ Projected growth in shipping in the future will depend heavily on growth in the production and consumption of raw materials and manufactured goods, and the location of these activities. Published shipping growth projections vary by up to 300% in 2050 depending on the specific assumptions used. The IEA's Baseline scenario projects slightly more than a doubling of shipping tonne-kilometres (tkms) between 2005 and 2050; in the High Baseline scenario, it triples. Assuming about a 25% reduction in energy intensity over this period, fuel use increases by 60% in the Baseline scenario and by 140% in the High Baseline scenario by 2050.
- ▶ Total CO₂ emissions from national and international transport in 2006 amounted to about 700 Mt, projected to rise to 1 085 Mt in 2050 in the Baseline scenario. A wide range of technical and operational efficiency measures exist to reduce fuel use and CO₂ emissions in shipping, with an estimated potential to reduce energy intensity by as much as 70% for some ship types. Overall, a reduction in energy intensity in the order of 50% appears feasible by 2050, which would double the projected improvement in the Baseline scenario.
- ▶ Low GHG biofuels could cut shipping CO₂ emissions substantially. For example, "biocrude" type fuels could provide relatively low-cost, low-GHG fuels for ships. In the BLUE Map scenario, biocrude or higher quality biodiesels such as biomass-to-liquids (BTL) fuels are assumed to be blended into petroleum fuel and to provide 30% of maritime transport fuel by 2050, with an average 85% reduction in CO₂ per litre (L) used compared to HFO. As discussed in Chapter 2, this will depend on the widespread availability of low-GHG, sustainable biofuels.

- ▶ Overall, shipping CO₂ emissions are reduced by 42% in the BLUE Map scenario in 2050 compared to the Baseline in that year, leaving them about 10% above 2005 levels.
- ▶ Deep cuts in CO₂ emissions from the shipping sector probably will only be achieved through the implementation of international policies to encourage reductions in fuel use. These could include the development of a ship design index and an operational index that could then be used to benchmark performance, with appropriate incentives targeting improvements. Shipping might also be included in an international CO₂ cap-and-trade system or in a CO₂ tax system, although the design of such systems on a global basis presents formidable challenges. Regional measures could include CO₂-differentiated fuel taxation or port fees, or the development of regional CO₂ cap-and-trade systems, although these would be less effective and less economically efficient than a global approach.

Background and recent trends in maritime transport

According to IEA data, national and international water-borne transport used an estimated 220 Mtoe of fuel in 2006.¹ About 83%, or 183 Mtoe, was used in international shipping. Some non-IEA estimates are significantly higher (Box 8.1). Shipping relies heavily on HFO. This accounts for approximately 77% of total maritime transport fuel and 85% of the fuel used by ocean-going ships. Most lighter marine distillate oil (MDO) is used by vessels engaged in river or coastal transport.²

Estimates of fuel use by ship category and size, recently developed for the IMO, are shown in Figure 8.1 (Buhaug *et al.*, 2008). Container vessels account for the largest share of fuel use. Tankers and bulk-transport vessels also account for significant amounts of fuel use, with passenger transport, via ferries and cruise ships, accounting for just over 10%. According to these data, more than 280 Mtoe was used in shipping in 2007. This is significantly higher than IEA estimates, partly as a result of different methodological approaches. The IEA approach provides only an estimate and probably underestimates total fuel use (Box 8.1). There is a need to improve data quality in this sector.

International maritime activity has grown significantly in recent years, doubling between 1985 and 2007 (Figure 8.2). The United Nations Conference on Trade and Development (UNCTAD)³ estimates that world sea-borne trade amounted to 49.4 billion tkm in 2006 (UNCTAD, 2007). Total containerised trade grew eight-fold between 1985 and 2007. In 2007, it represented 16% of all maritime trade by weight and a much larger share by value. The average CO₂ emission use per

1. The IEA is still developing its understanding of maritime transport. This chapter therefore draws on data from a range of sources. The chapter draws heavily on a recent draft report prepared by Philippe Crist of the International Transport Forum of the OECD (Crist, 2009), with permission.

2. Specialised liquefied natural gas (LNG) tankers use a fraction of their cargo to power their steam turbines.

3. UNCTAD publishes a yearly review of International Maritime Transport. The 2007 edition of this review serves as the basis for this section.

tonne of freight delivered⁴ by sea has slightly decreased between 1985 and 2007 with the advent of more efficient engines and vessels, despite much higher volumes of energy-intensive containerised trade.

Box 8.1 ▶ **Fuel use and CO₂ emissions from maritime transport are uncertain**

The IEA approach to measuring fuel use in international shipping is based on statistics on the sale of fuel to vessels for which the next port-of-call is outside the country in which the fuel is purchased. On this basis, international shipping accounted for 183 Mtoe and 583 Mt of CO₂ from fuel combustion in 2006. These fuel statistics were originally collected to ensure that IEA member countries did not have to hold reserves against fuel stocks not kept for domestic use. This was particularly important for countries such as the Netherlands, where sales to international shipping are a very large part of total oil sales.

It is likely that the IEA international shipping data underestimate total international maritime fuel use, in particular because:

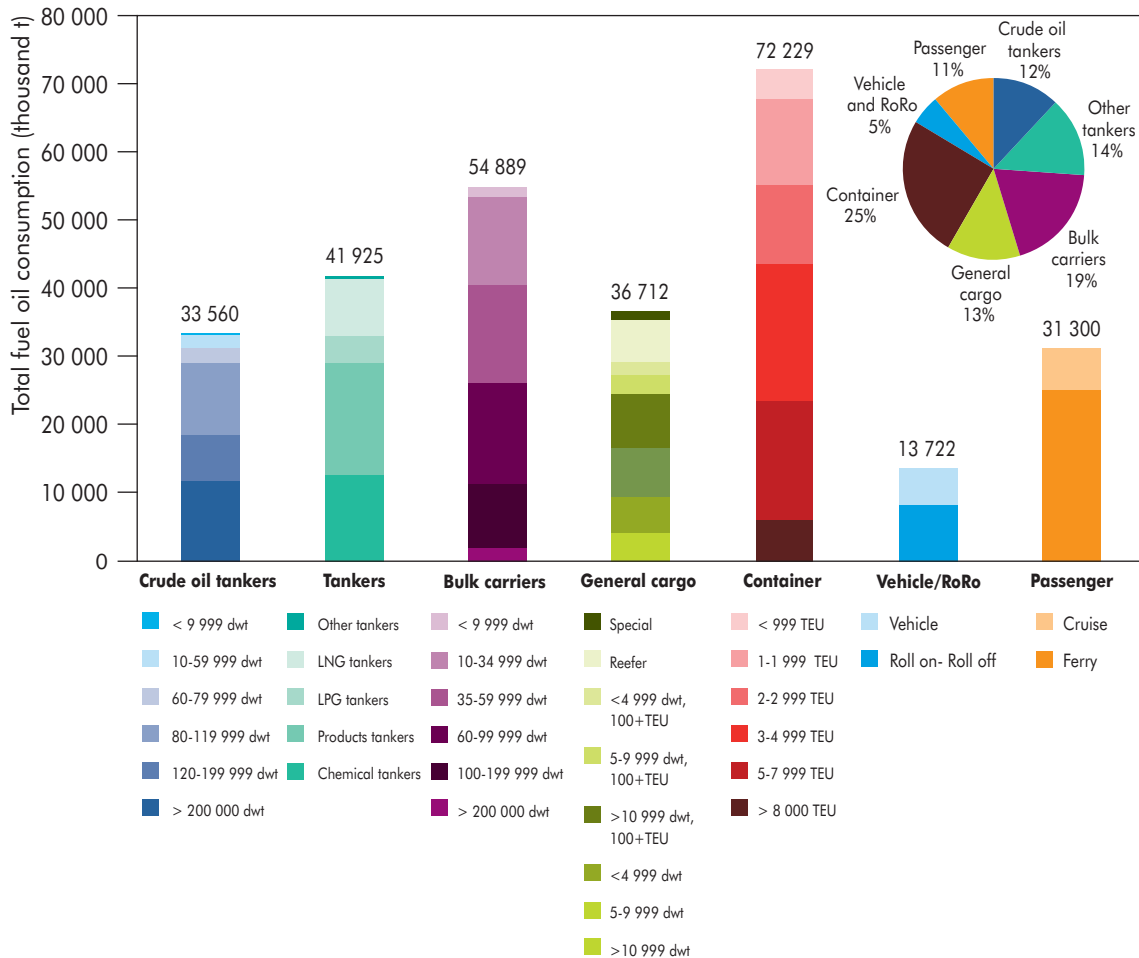
- Although OECD countries have an obligation to report bunkering data to the IEA, data for non-OECD countries are reported voluntarily and may be of variable quality.
- Data on international marine bunkers for major non-OECD countries, such as Russia, are missing. In some cases, they may have been reported as exports.
- The importance of non-OECD countries in international marine bunkering may have been increasing. So any gap between actual and reported bunker use may be growing over time.

In 2006, there was a reporting imbalance between imports and exports in the global fuel oil market of about 60 Mtoe. This imbalance has been growing since the early 1980s when it was around 20 Mtoe to 30 Mtoe. There could be a number of reasons for this imbalance, but one might be under-reporting of marine fuel imports. If virtually all of the missing 60 Mtoe was due to this, it would suggest shipping emissions were being underestimated by about 190 Mt CO₂. But other reasons for the difference are also possible, so this represents an upper bound and is very uncertain.

Recently, several studies have sought to estimate maritime fuel consumption and CO₂ emissions by modelling the world fleet and accounting for its activity. Some of this work has incorporated detailed manufacturers' data on engines, rated power, operating cycles, actual vessel travel patterns and overall vessel energy consumption (Eyring et al., 2007; IMO, 2007). Other studies have looked at historical factors that affect shipping activity and used fleet-average models (Endresen et al., 2007). Both approaches result in higher fuel use and higher CO₂ emission estimates than the IEA figures.

Work recently commissioned by the IMO (Buhaug et al., 2008) estimated that all ocean ship activity produced 1 019 Mt of CO₂ in 2007 of which 843 Mt resulted from international shipping. This is nearly 50% higher than the IEA estimate of 583 Mt CO₂. It also falls outside the range that could be accounted for by the known discrepancy between IEA's fuel oil import and export data. It is difficult to reconcile these very different estimates. More work is needed to resolve this important issue.

4. Here measured by proxy using CO₂ emissions from international maritime bunkers divided by the total number of tonnes of freight delivered in any given year.

Figure 8.1 ▶ Fuel use by vessel category, 2007

Note: Excludes fishing, service and offshore supply vessels.

Source: Adapted from Buhaug *et al.*, 2008.

Key point

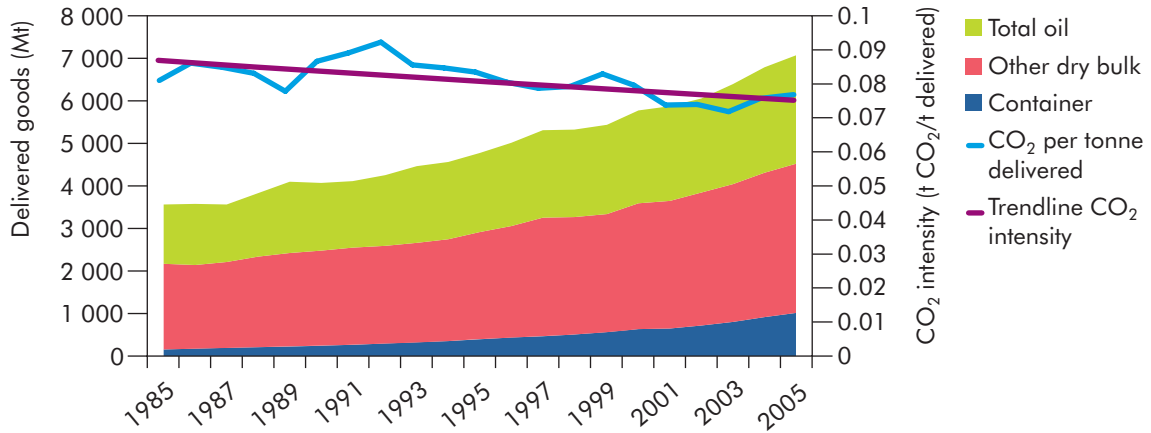
Container shipping accounted for the most maritime energy use in 2007, followed by bulk goods carriers.

Growth in international maritime transport has outstripped GDP growth (Figure 8.3). International trade continues to drive maritime activity, increasingly by exports from emerging export markets such as China. In 2006, world merchandise trade grew by 8% – double the rate of world GDP growth – contributing to robust growth in the container traffic that carries much of the world’s manufactured output between continents.

Maritime trade is expected to continue to grow alongside rising demand for oil, coal, steel and other primary resources. This demand has already led to more distant sourcing of these resources and higher GHG emissions. For example, China has started to source iron ore from Brazil and Africa as Australian output has plateaued.

China has also recently become a net importer of coal. As a result, countries such as Japan, Korea and Chinese Taipei, which have traditionally imported coal from China will have to turn to more distant Australian and Indonesian supplies.

Figure 8.2 Trends in maritime transport volumes and related CO₂ emissions

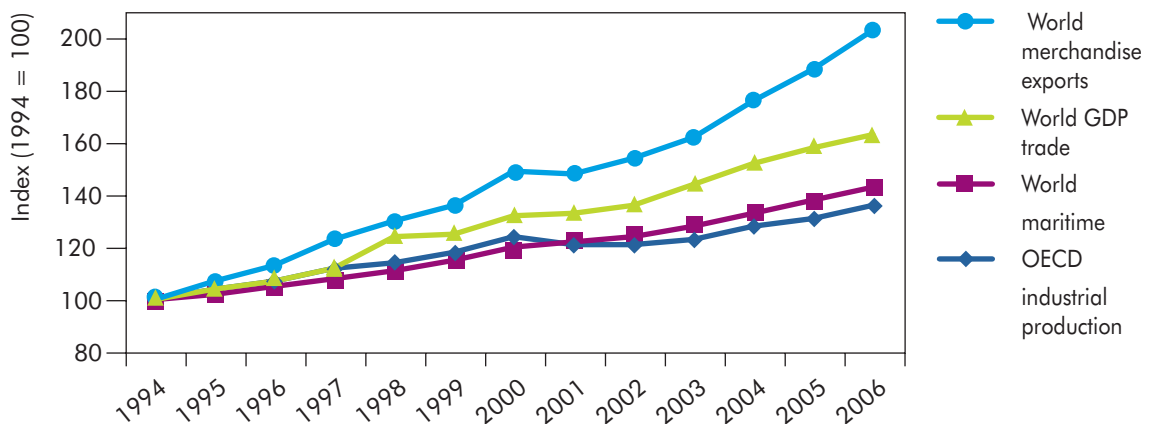


Sources: Clarksons, Global Insight, Drewry and IEA.

Key point

Though transport volumes of major categories of shipped goods have doubled in the past 20 years, CO₂ intensity has fallen by about 15%.

Figure 8.3 Growth in maritime trade, world trade and GDP (indexed), 1994-2006

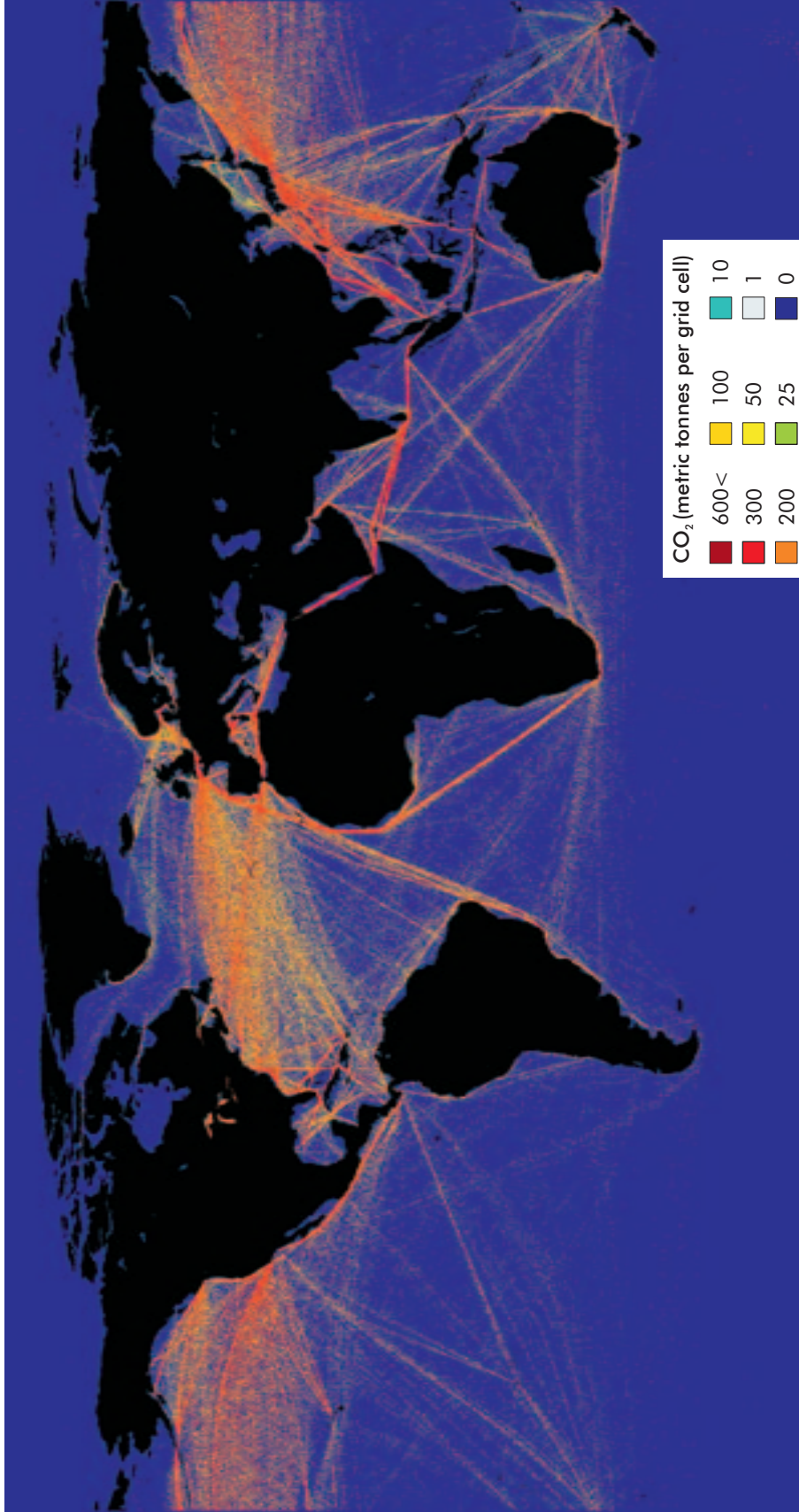


Source: UNCTAD, (2008).

Key point

World trade and maritime trade have grown more quickly than world GDP.

Figure 8.4 ▶ Global maritime traffic and CO₂ emissions, 2001



Source: Data from Wang, 2007, cartography by ITF.

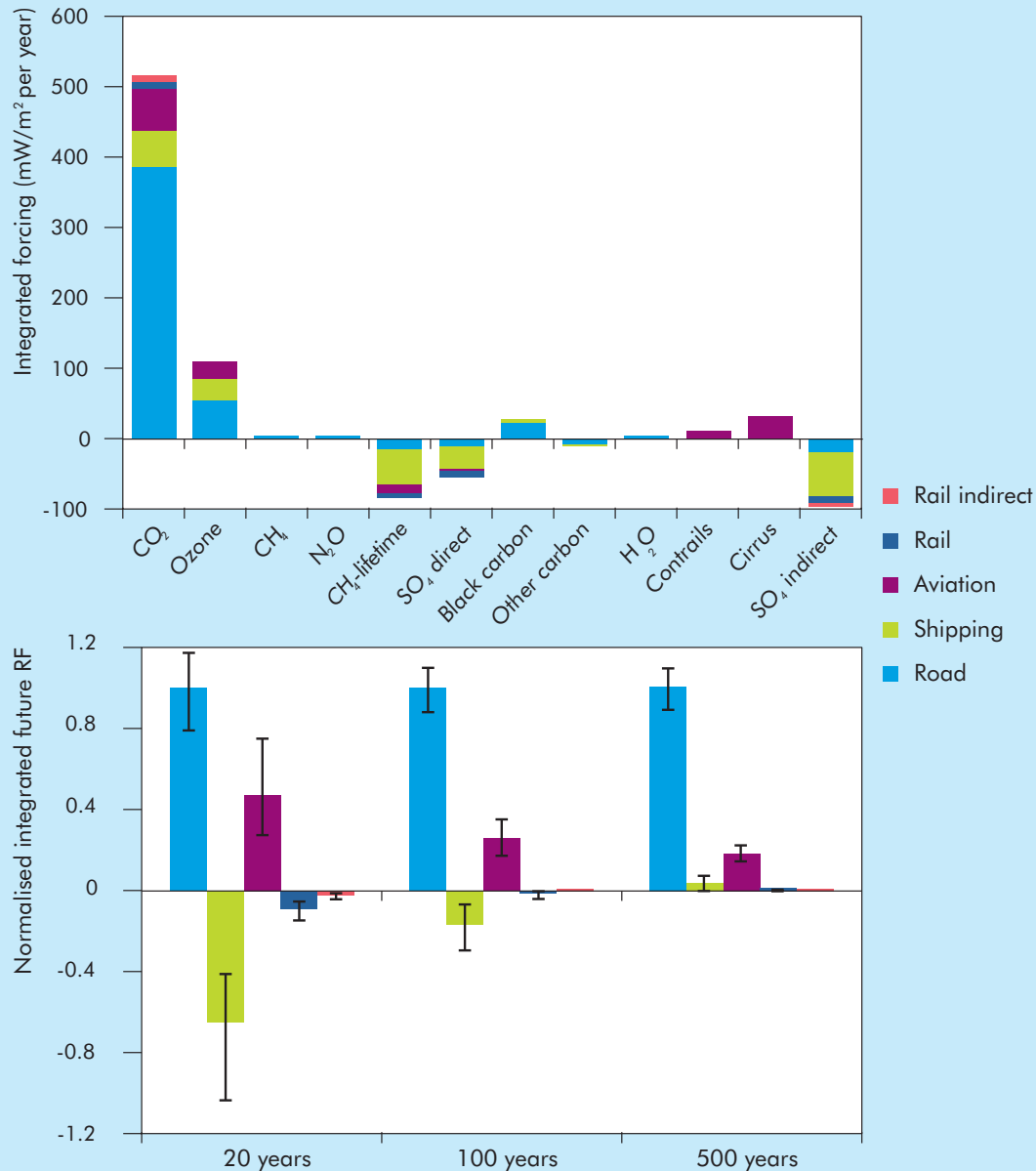
Key point

Most maritime trade follows well established routes, with most CO₂ emitted in a few key shipping lanes.

Box 8.2 ▶ Maritime transport: net cooling impacts?

Although some studies have estimated the RF of GHGs in the aviation sector (Box 7.1), few have assessed the RF effect of the transport sector as a whole. A recent study by the Centre for International Climate and Environmental Research-Oslo (CICERO) uses assessments of RF for different gases relevant to transport emissions and their effects, essentially on the lines of those

Figure 8.5 ▶ Integrated radiative forcing of current emissions by substance and by transport mode



Source: Fuglestedt et al., 2007.

Key point

The importance of shipping in the physics of climate change is substantial and should be taken into account for the climate negotiations.

used by IPCC (2007), to estimate the overall impact of the road, rail, aviation and shipping transport sectors (Fuglestedt et al. 2008). The study estimated cumulative emissions since pre-industrial times and the integrated RF of recent (e.g. year 2000) emissions over 20-year, 100-year and 500-year time scales.

Accounting for all positive and negative RF for the period 1875 to 2000, the study found that road transport has had the largest warming impact. The next largest warming subsector is aviation. Shipping is estimated to have a net negative RF, i.e. to have had a cooling impact, over the same period. This is largely due to the direct and indirect cooling impact of sulphur emissions and to the contribution of shipping NO_x emissions to CH_4 reductions. However, there are still significant uncertainties regarding the RF impacts of some of these pollutants, such as O_3 and black carbon. Much more research is needed to better understand the net RF impacts of the full range of pollutants that may have an impact on the climate.

Figure 8.4 shows the principal freight shipping routes based on data from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and Automated Mutual-Assistance Vessel Rescue System (AMVER) databases.

The climate impacts from shipping are linked to the by-products of HFO, and to a lesser extent, MDO combustion. These include CO_2 and several other pollutants such as NO_x , CO, and black carbon. CO_2 is the most significant GHG produced by shipping and the remainder of this chapter focuses on this, although the climate impact of other HFO and MDO by-products should not be ignored (Box 8.2).

Energy efficiency of maritime transport

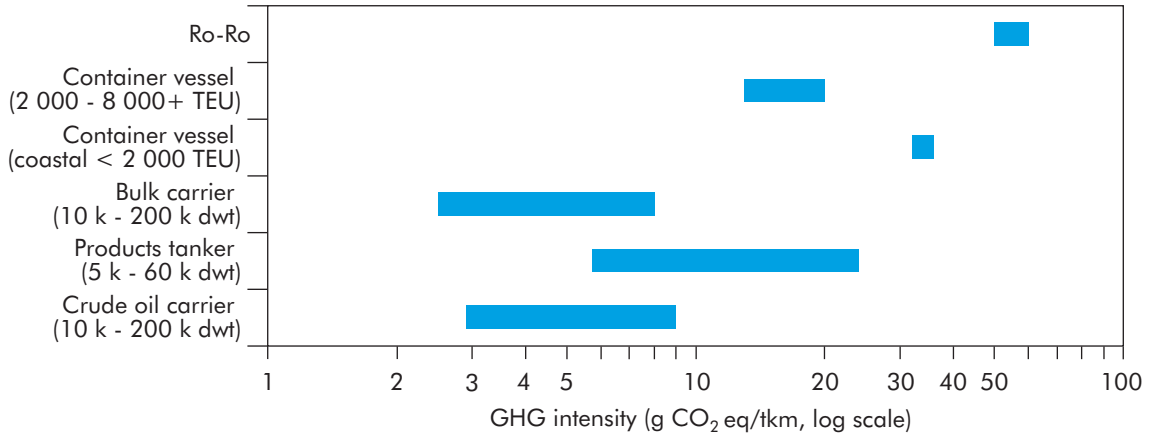
Shipping offers large economies of scale in goods movement. Vessels can carry large volumes of cargo, and their energy use and CO_2 emissions per unit of freight moved are relatively low. But assessing the energy or CO_2 efficiency of the shipping sector is not straightforward.

Trade imbalances and operating cycles result in average efficiencies that are less than the relevant vessels' fully loaded efficiency. For example, oil tankers typically run full to their destination port and return with empty tanks under ballast. Similarly, trans-Pacific container vessels tend to have a higher loading of full containers on eastbound journeys than on westbound ones. Estimates of average load factors for various vessel types range from 50% for tankers, to 60% for bulk transporters, to 70% for container ships. Fuel use is also influenced by specific power needs, with some vessels requiring greater auxiliary power (e.g. for powering cargo climate-control systems), while others (such as container vessels) require more powerful engines for higher speeds. Apart from engine efficiency, hydrodynamic drag is the primary source of energy loss for ships. Hull shape and ship speed are both critical factors determining the efficiency of shipping.

Figure 8.6 indicates a range of CO_2 intensities for different types of maritime freight transport. Not all modes are interchangeable in all contexts. For example, bulk oil products not transported by sea are more likely to be transported by pipeline

rather than by road or rail, and the non-maritime carriage of bulk dry goods will be more likely to occur by rail rather than by road. But for much long-distance freight, especially between continents, maritime transport is the only available transport option.

Figure 8.6 ► GHG intensity of selected maritime freight transport modes



Source: ITF estimates and Buhaug *et al.*, 2008.

Key point

The least GHG-intensive maritime transport is for bulk goods and tankers, often below 10 g of CO₂-eq per tkm.

Projected activity increase in shipping

The IEA does not, at this time, make projections of shipping activity, but such projections are available from several sources. The IMO recently made estimates of future fuel use and CO₂ emissions from shipping for 2020 and 2050⁵ (Buhaug *et al.*, 2008).

The IMO study uses a model based on three variables: economic activity, transport efficiency and embodied fuel energy. These, in turn, are related to a number of underlying variables such as population, regional economic growth, oil prices and technical efficiency improvements. Macro-economic, energy use and demographic variables are drawn from the *IPCC Special Report on Emissions Scenarios* (IPCC, 2000) and extrapolations of historic trends are adjusted according to specific factors that are likely to have an impact on maritime transport demand. These factors include:

- New gas pipelines from Myanmar to China in the 2030s.
- New gas pipelines from the Middle East to India in the 2030s.

5. Another recent study by the Japanese Ocean Policy Research Foundation (OPRF) (2008) has also estimated future levels of maritime activity and CO₂ emissions. The OPRF and the IMO studies are different in approach and in some of their findings. But since the IMO study has sought to incorporate the findings of the OPRF study, the IMO findings are used in this analysis as the main basis for discussing future maritime activity and emission trends.

- New gas pipelines from Russia to China in the 2010s.
- Expansion of the North Africa-Europe Pipeline in the 2030s.
- Modernisation of the Trans-Siberian Railroad to accommodate container traffic in the 2030s.
- Opening of the Arctic Sea Route between East Asia and Europe⁶ in the 2040s.
- Increase in scrap iron recycling equivalent to a 5% reduction in ore production.

These adjustments reduce maritime transport demand projections by up to half of what might otherwise have been expected based on the extrapolation of past GDP-related maritime transport activity trends.

Based on a range of six IPCC scenarios, Buhaug *et al.*'s resulting estimates for future activity indexed to 2007 tkm are set out in Table 8.1.

Table 8.1 ► Maritime traffic forecasts from IMO

Year and shipping category	IPCC SRES scenario (Index, 2007=100)					
	A1B	A1F	A1T	A2	B1	B2
2020						
Ocean-going shipping	131	131	131	121	120	114
Coastal shipping	131	132	131	126	120	120
Container shipping	194	193	195	176	173	165
Average all ships	146	146	146	135	133	127
2050						
Ocean-going shipping	245	245	245	190	185	155
Coastal shipping	245	250	245	215	185	185
Container shipping	900	875	905	645	615	525
Average all ships	402	397	403	302	288	247

Source: Buhaug, *et al.*, 2008.

The six different IPCC scenarios show a range of possible futures, with shipping increasing by between 30% and 45% from 2007 to 2020, and by between 150% and 300% from 2007 to 2050. The IMO study projects that, within this total, container activity will show the strongest growth – of 65% to 95% by 2020 and 400% to 800% by 2050. Growth in container movements has particularly important GHG repercussions as the installed power on container vessels is higher on average as they have higher speed requirements than most other types of vessels.

Larger ships are more fuel efficient at constant load factors than smaller vessels. So the IMO projections assume increases in fuel efficiency from increases in average ship size, from running ships more slowly, and from technical improvements to new vessels. The IMO Baseline projections assume no increases in the regulation of CO₂ emissions or fuel consumption.

6. Enabled by the retreat of the Arctic ice cap.

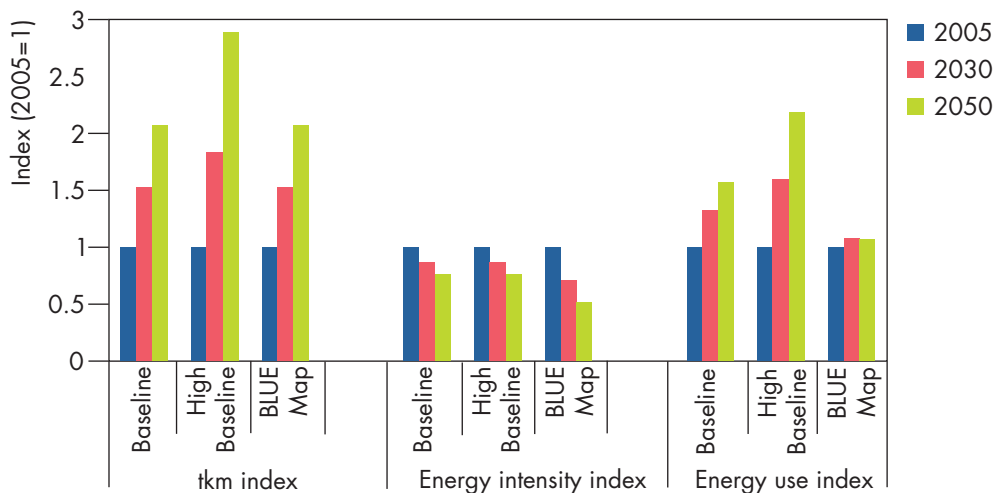
The IEA has incorporated many of these assumptions into a simplified framework to project maritime transport activity, intensity, fuel use and CO₂ emissions. These are presented below.

IEA scenarios of future maritime transport energy use and CO₂ emissions

The IEA has developed Baseline and High Baseline projections of the energy use and CO₂ emissions of international shipping based on the IMO projections, reflecting past relationships between GDP growth and shipping activity and fuel use. These reflect the World Energy Outlook 2008, WEO 2008 (IEA, 2008a) projections for income growth and expected volumes of international freight movement to 2030. These projections fall at the lower end of the range implicit in the IPCC-based projections used by Buhaug *et al.*

The outcomes of these projections are shown in Figures 8.7 and 8.8. Figure 8.7 shows activity growth, energy intensity and energy use for international shipping for the Baseline, High Baseline and BLUE Map scenarios all indexed to 2005 levels. In the Baseline scenario, activity roughly doubles by 2050, energy intensity improves by 25% and, as a result, energy use increases by about 50%. In the High Baseline scenario, activity growth nearly triples. So, with the same energy intensity improvement as the Baseline, energy use more than doubles. In the BLUE Map scenario, activity growth matches the Baseline but energy intensity is cut by half, resulting in essentially unchanged energy use over time. In the BLUE Map scenario, the rate of reduction in energy intensity is assumed to match the rate in activity growth. This is a very challenging proposition, as the BLUE Map scenario assumes Baseline activity growth. If activity growth is closer to that in the High Baseline scenario, it will be virtually impossible to achieve sufficient improvements in energy intensity to offset that volume growth.

Figure 8.7 ▶ IEA projections of international shipping activity, energy intensity and energy use by scenario



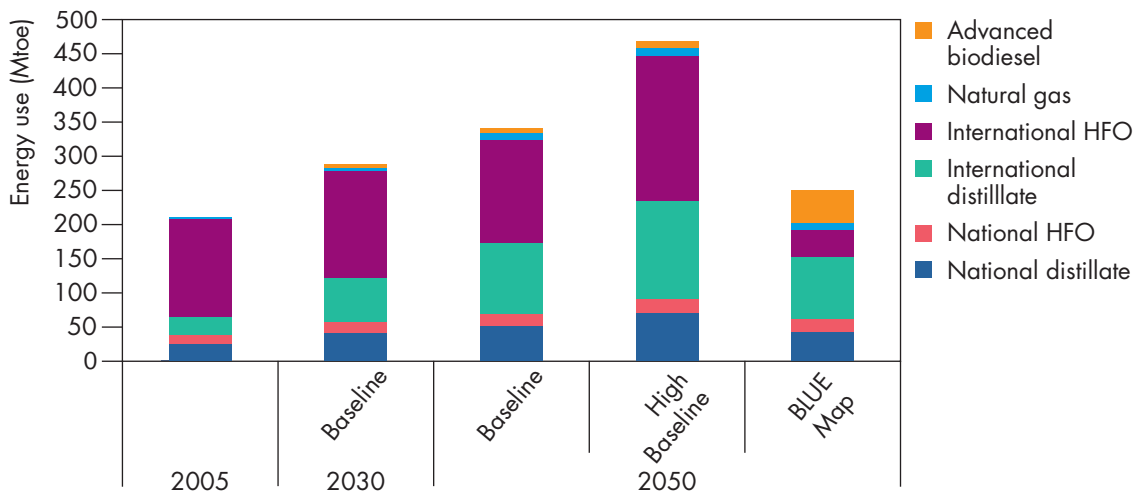
Key point

In the BLUE Map scenario, energy intensity is cut by half and energy use remains nearly flat through 2050.

Figure 8.8 shows the projected consequential demand for different fuels, using IEA data, for both national and international shipping. In the Baseline scenario, fuel use increases from about 210 Mtoe in 2005 to about 290 Mtoe by 2030 and nearly 350 Mtoe by 2050, reflecting a decoupling of shipping growth from GDP growth as economies expand more in information sectors than material sectors. In the High Baseline scenario, past growth rates are assumed to decouple far less than in the Baseline scenario, and shipping energy use reaches 450 Mtoe by 2050. In both cases, most of the fuel used is HFO, although the share of marine distillate is assumed to increase, and in the BLUE Map scenario, biofuels reach 30% of international fuel use by 2050. For shipping within national borders, total fuel use remains far lower than for international shipping, reaching about 70 Mtoe in 2050 in the Baseline scenario and about 90 Mtoe in the High Baseline scenario.

CO₂ projections (not shown) generally closely follow the fuel use projections except in the BLUE Map scenario in which the increased use of second-generation biofuels would reduce the CO₂ emissions attributable to the petroleum fuels they displaced by 80% to 90%. This is dependent on successful development of such fuels, and on the availability of enough sustainably produced feedstocks to meet demand from a number of competing sectors. If achievable, a 30% biofuels share would provide about a 25% reduction in CO₂ emissions in the BLUE Map scenario, on top of that already projected as a result of reductions in energy use. But as described in Box 8.1, other pollutants also have GHG effects. A fuller analysis of various GHGs and their combined impacts is needed. This is beyond the scope of the IEA's work to date.

Figure 8.8 ▶ International shipping energy use by scenario



Note: Figure based on IEA data for 2005.

Key point

With advanced biofuels, maritime petroleum fuel use in 2050 is lower than in 2005.

Potential for energy savings and CO₂ reductions in maritime transport

This section reviews the opportunities for reducing energy use and GHG emissions from shipping through both technological and operational improvements. These opportunities are assessed in terms of the percentage reductions they can achieve, with rough estimates of the associated abatement costs where possible.

The technological opportunities to reduce fuel consumption in ships can be broadly divided into five categories: engine and transmission technologies; auxiliary power systems; propulsion systems; superstructure aerodynamics; and hull shapes.

Ship propulsion

The fuel used by ships is directly linked to their engine capacity and power output, the vessel's size and its operational activity, including speed. Fuel consumption generally increases as a function of the cube of the vessel's speed, as increased power output is required to move the mass of the vessel against hydrodynamic and aerodynamic resistance.

Ships must overcome three resistances in order to move forward:

- Frictional resistance, such as the resistance generated by the interface between the hull and water.
- Residual resistance, such as the resistance generated by waves against the hull and by the trailing eddy behind the vessel.
- Air resistance, determined by the aerodynamic characteristics of the vessel's superstructure.

Frictional resistance: Frictional resistance is the main resistance that must be overcome by slower-moving vessels. It is a function of the area, the shape and the surface resistance characteristics of the part of the hull that is below the water line.⁷ Frictional resistance increases at a rate more or less equal to the square of the vessel's forward speed. For large bulk carriers and tankers, frictional resistance represents 70% to 80% of overall resistance. This is less than 40% for higher speed vessels such as container ships (MAN Marine, 2007). Hull fouling due to the surface accretion of barnacles, algae and sea plants can increase this resistance by up to 40%. Fouling increases with ship operation and can be reduced by hull cleaning or repainting.

Residual resistance: At slow speeds, wave resistance is proportional to the square of the vessel's speed, but it rises much more quickly than this at higher speeds. At some point for any vessel, further power increases result in no increase in speed as the vessel hits what is known as the "wave wall". Residual resistance can represent as little as 8% of the overall resistance for low-speed ships or as much as 60% of

7. Partly laden vessels experience less frictional resistance than fully loaded vessels because they have less hull under the water.

overall resistance for faster vessels. Shallow water operation also leads to higher residual resistance.

Air resistance: In calm conditions, air resistance is proportional to the square of the vessel's speed and a function of the cross-sectional area of the vessel facing the wind. Air resistance is a relatively minor factor when compared to water (hydrodynamic) resistance, representing around 2% of overall resistance at slow speed, rising to potentially more than 10% of the overall resistance of fast-moving vessels with large cross-sections.

Propellor and engine efficiency also affect the overall efficiency of the vessel.

Propeller efficiency: The blades of the propeller(s) driving a vessel forward also experience resistance. Surface resistance, and detached flow and eddy effects, are amplified by the fact that propellers are typically operating in a turbulent wake field created by the vessel's hull. As a result, there is a non-linear and decreasing relationship between the amount of power supplied to the propeller shaft, the resultant propeller thrust, and the vessel's speed. Propeller surfaces also degrade over time, through fouling and corrosion, becoming rougher and requiring greater power output for a given speed.

Marine engines: Most ocean-going cargo vessels are powered by extremely large, slow-speed, two-stroke engines that are coupled directly to the propeller shaft without a clutch or reduction gears. Such engines have high power outputs of up to nearly 85 MW and are relatively efficient, delivering about 50% of the fuel energy directly to the propeller shaft. They are adapted to burn directly injected HFO.

Some very large cargo carriers, and most passenger ships and ferries, require greater acceleration and are built with medium-speed, four-stroke engines running on MDO or HFO fuels. The combination of high-temperature combustion and low quality fuels leads to very high rates of NO_x and SO_x emissions compared to current land-based diesel engines that have already gone through several pollution reduction design cycles.

Ocean-going vessels operate on a range of very different duty cycles. Some, such as those operated by ferries and roll on-roll off (RoRo) transporters, are characterised by multiple short stops. Others, such as those of oil and other tankers, involve very long, heavily laden, outbound trips with ballast-only returns. These operating cycles significantly influence engine power requirements and auxiliary power needs and, as a consequence, fuel consumption and CO₂ emissions. They also have an impact on operational factors, such as routing and port time, that also are linked to fuel use and CO₂ emissions. Vessel speed is paramount for some applications such as container shipping. Auxiliary power requirements can be an important element of overall fuel use, for example for vessels with refrigerated cargoes. Cargoes can change ownership en route, leading to trip diversion and sub-optimal routing. Other vessels are subject to time constraints that may require navigating in heavy weather conditions. Some vessels, e.g. ice class vessels, may be configured to trade in specific conditions. All of these duty-cycle related factors can have an important impact on the CO₂ emissions of individual vessels.

Review of technology and operational fuel saving strategies

Fuel savings and CO₂ emission reductions can be achieved in a number of different ways in the maritime transport sector. In the following analysis, these options are broadly grouped into strategies impacting on the design of vessels, engines and propulsion systems, other technology-related strategies, and operational measures. The emphasis is on measures that can be implemented relatively quickly and an indication is given as to an option's likely payback period, ranging from short (one to three years) to long (more than 15 years). Given the lack of robust data, no attempt is made to estimate either costs or marginal abatement costs.⁸

As not all options make sense for all vessels, an indication is given as to which class of vessels are most likely to benefit from each approach. Each option is characterised as to whether it must be incorporated into the vessel design process, and is thus only applicable for new builds, or whether it can be applied to existing vessels either through technology retrofits or through changes in operational procedures. The upper bound of the overall fuel savings and CO₂ reductions that may result on average from the implementation of each measure is provided, measured as a percentage of the fuel use or CO₂ emissions attributable to that aspect on a vessel not implementing the relevant option.

Overall vessel design

Overall design strategies that affect the size of the vessel, its displacement, its dimensions, its handling characteristics under loaded and ballast conditions, and its hull configuration all have an impact on fuel use and CO₂ emissions for specific duty cycles.

Table 8.2 ▶ Overall vessel design options

Strategy	Description	Fuel efficiency gain	New build	Retro-fit	Operational
<ul style="list-style-type: none"> ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply 					
Efficiency of scale ● ● ● ●	Increasing vessel size. Larger vessels will be more efficient in terms of energy expended per tkm. Regression analysis of recent new-builds indicates that an increase in vessel size of 10% will result in ~4% greater specific efficiency. Short payback.	<4%	<input type="checkbox"/>		
Design for reduced ballast operation ● ● ● ● ●	Designing a vessel to operate with less ballast can offer important efficiency gains, reducing the area of the hull under water and reducing resistance. Short payback.	<7%	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

8. These estimates of fuel efficiency improvements were developed by ITF, using data from (Wartsila, 2008), (Green, Winebrake and Corbett, 2008), and (Bond, 2008).

Table 8.2 Overall vessel design options (continued)

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Lightweight construction ● ● ● ● ●	Replacement of steel by lighter weight alternatives in non-structural elements of vessel design can lead to fuel efficiency gains. But this can be expensive and care must be taken to ensure that direct CO ₂ reductions from reduced fuel consumption are not more than offset by the CO ₂ emitted in mining and smelting lighter weight alternatives. A 20% reduction in weight will result in approximately 9% lower power requirements for a given vessel configuration and service speed. Short payback.	<7%	<input type="checkbox"/>		
Optimum hull dimensions ● ● ● ● ●	Optimising hulls for reduced frictional resistance can have a significant impact on fuel consumption. Designing a typical product tanker to be 10% to 15% longer can reduce engine demand by ~10% for a given speed. This is an expensive option as longer vessels cost more. Long payback.	<9%	<input type="checkbox"/>		
Low-profile hull openings ● ● ● ● ●	Turbulence from interrupted water flows at hull openings, such as bow thrusters, tunnels and sea chest openings, can increase resistance and fuel consumption. Designing these openings to reduce flow disturbance can improve fuel efficiency. Short payback.	<5%	<input type="checkbox"/>	<input type="checkbox"/>	
Interceptor trim plates ● ●	These are vertical underwater extensions at the rear of a hull that channel the high-pressure flow behind the propellers downwards, thus creating a lift effect. An option suitable for relatively high-speed vessels such as Ro-Ros and ferries. Short payback.	<4%	<input type="checkbox"/>	<input type="checkbox"/>	
Aft waterline extension ● ● ●	This is a tapered aft extension of the vessel at the waterline that reduces wake turbulence. It can be combined with an interceptor trim plate for better results. Short payback.	<7%	<input type="checkbox"/>	<input type="checkbox"/>	
Shaft line alignment ● ● ●	Aligning propeller shafts to minimise turbulent flow and frictional resistance can reduce overall power demand and energy consumption. Short payback.	<2%	<input type="checkbox"/>		
Skeg shape – trailing edge ● ● ● ● ●	The skeg is an extension of the hull leading up to the propeller shaft line and disc. Optimising the form of the skeg to deliver low-speed but non-turbulent flows to the propeller disc can reduce engine power output requirements. Short payback.	<2%	<input type="checkbox"/>		
Air lubrication ● ● ● ●	Pumping compressed air into a recess along a vessel's hull can reduce frictional resistance by lubricating the hull-water contact area. This can reduce fuel use by up to 15% for large-surfaced hulls on slower-speed vessels (e.g. tankers), even after allowing for the additional auxiliary power needed. Fuel savings for container vessels and LDV carriers are about half as much. Medium payback.	<15%	<input type="checkbox"/>		
Bulbous bow ● ● ● ●	A bulbous below-the-waterline extension of the bow can improve water flow around the hull and reduce drag for large vessels operating within commercial speed ranges.	<20%	<input type="checkbox"/>		

Engine design

Engine design, size and power output determine fuel use and emissions. During the vessel design phase, it is important that the most efficient engine is specified for the vessel's size and intended duty cycle. At present, there are no mandatory fuel economy standards for maritime engines.

NO_x emissions and engine fuel consumption are inversely related. As a result, it can be expected that the achievement of the mandatory rules and standards relating to NO_x emissions laid down by MARPOL⁹ will entail an increase in fuel consumption and in consequential CO₂ emissions.

Table 8.3 ▶ Engine design options

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Engine derating ● ● ● ● ●	Marine engine designers can tune engines to best fit the task for which they are designed. Adding an additional cylinder and permanently operating the engine at a lower speed (known as de-rating) can reduce fuel consumption for a given vessel speed. Medium payback.	<3.5%	<input type="checkbox"/>	<input type="checkbox"/>	
Diesel electric drives ● ● ●	Substituting coupled electric drives for the traditional direct engine-propeller shaft connection can deliver substantial savings, especially where frequent changes in shaft load and operating profiles are required (e.g. with frequent manoeuvring). Medium payback.	5-30%	<input type="checkbox"/>		
Combined diesel-electric and diesel-mechanical drives ● ●	Combining electric drives for part-load operation and fully coupled mechanical drivetrains for full load operation can optimise engine performance for vessels with variable engine load requirements. Long payback.	<4%	<input type="checkbox"/>		
Waste heat recovery ● ● ● ● ●	Capturing and re-converting engine exhaust gas heat into electric energy can reduce direct engine fuel requirements for electric-coupled propulsion systems or reduce auxiliary engine requirements. Recovered heat can also be used for other shipboard functions (e.g. fuel heating). Medium payback.	<10%	<input type="checkbox"/>	<input type="checkbox"/>	

9. MARPOL is the International Convention for the Prevention of Pollution From Ships, a convention initially implemented during the 1970s and focused on reducing pollution of the seas, including dumping, oil and exhaust pollution.

Table 8.3 ▶ **Engine design options** (continued)

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Enhanced engine tuning and part-load operation ● ● ●	Tuning engines to operate most efficiently in the most commonly used load ranges can reduce overall fuel use even at the expense of an offsetting fuel use penalty for seldom-used operations. Short payback.	<4%	<input type="checkbox"/>	<input type="checkbox"/>	
Common rail engine ● ● ● ● ●	Common rail fuel-injection systems in marine engines exhibit the same benefits as automotive common rail technologies in that combustion can be optimised over the entire engine operating field. Short payback.	<1%	<input type="checkbox"/>	<input type="checkbox"/>	

Table 8.4 ▶ **Propulsion system options**

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Wing thrusters ● ● ●	Combining twin wing thruster propellers to a single shaft main propeller results in fuel savings compared to a twin-shaft design. Medium payback.	<10%	<input type="checkbox"/>		
Counter-rotating propellers ● ● ● ● ●	Coupled counter-rotating propellers allow for the rearmost propeller to recover some of the energy from the slipstream of the forward propeller.	<12%	<input type="checkbox"/>		
Optimised propeller-hull interface ● ● ● ● ●	Optimising the hull to the propeller can reduce hull-propulsion system interference and improve fuel consumption. Short payback.	<4%	<input type="checkbox"/>		
Propeller-rudder Unit ● ● ●	Optimising the rudder design and co-ordinating the rudder and propeller shapes (e.g. with a rudder bulb) can reduce drag and save fuel. Medium payback.	<4%	<input type="checkbox"/>	<input type="checkbox"/>	
Optimised propeller blade sections ● ● ● ● ●	Propeller blades designed for reduced friction and cavitation reduce fuel consumption. Short payback.	<2%	<input type="checkbox"/>	<input type="checkbox"/>	
Propeller tip Winglets ● ●	Just as winglets reduce trailing turbulence on aircraft wings, so too do propeller tip winglets on ships.	<4%	<input type="checkbox"/>	<input type="checkbox"/>	
Propeller nozzle ● ●	A propeller nozzle is a wing-section shaped ring circling the propeller which reduces trailing turbulence up to speeds of 20 knots.	<5%	<input type="checkbox"/>	<input type="checkbox"/>	

Table 8.4 ▶ Propulsion system options (continued)

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Propeller Efficiency Monitoring ● ● ● ●	Monitoring the operational efficiency variables of the propeller such as speed, torque and thrust and modifying engine output accordingly can enable operational fuel savings. Short payback.	<4%	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Efficient Propeller Speed Modulation ● ● ● ●	Operating controllable-pitch propellers at constant speed over a wide range of ship speeds is inefficient. Reducing propeller rotational speeds to match ship speed rather than modulating propeller pitch can deliver fuel savings.	<5%	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pulling Thruster ● ● ●	Combining thrusters with a forward-facing propeller can reduce fuel use for vessels requiring frequent operation at variable loads.	<10%	<input type="checkbox"/>		
Wind power: Flettner rotor ● ●	A Flettner rotor is a spinning vertical rotor that converts prevailing wind into propulsive energy. This harnesses wind power irrespective of its direction and can considerably reduce fossil fuel use. Long payback.	<30%	<input type="checkbox"/>	<input type="checkbox"/>	
Wind power: kites and sails ● ● ● ●	Traditional sail configurations with advanced fabric or composite materials and/or kites attached to the bow can harness wind power for forward propulsion. Sails require available deck space. Long payback.	<20%	<input type="checkbox"/>	<input type="checkbox"/>	

Table 8.5 ▶ Other technology strategies

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Low-loss electric drive ● ● ●	Consolidating power transformation and reducing the number of transformers for electric drives reduces distributional losses. Especially useful for vessels whose duty cycles require extensive part-load operation. Medium payback.	<2%	<input type="checkbox"/>		
Hybrid auxiliary power generation ● ● ● ● ●	Hybridising auxiliary power generation can deliver important auxiliary engine fuel consumption reductions and enable the use of renewable energy sources such as wind or solar power. Short payback.	<2%	<input type="checkbox"/>		
Variable-speed electric power generation ● ●	Using variable speed generators can enable capacity to be better aligned with onboard power needs. Medium payback.	<3%	<input type="checkbox"/>		

Table 8.5 ▶ Other technology strategies (continued)

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Energy-saving lighting and heating ●	More efficient lighting and heating can reduce auxiliary power needs.	<1%	<input type="checkbox"/>	<input type="checkbox"/>	
Enhanced power management ● ● ● ● ●	Managing onboard power requirements efficiently can lead to significant overall fuel savings. Medium payback.	<5%	<input type="checkbox"/>		<input type="checkbox"/>
Solar power ● ● ●	Generating electricity and heat via on-deck solar panels reduces fuel consumption related to auxiliary power and heating requirements. Medium payback.	<4%	<input type="checkbox"/>	<input type="checkbox"/>	
Variable-speed pumps ● ● ● ● ●	Using variable-speed engine cooling pumps that match cooling water flow to engine cooling needs can save energy.	<1%	<input type="checkbox"/>	<input type="checkbox"/>	
Automation ● ● ● ● ●	Advanced automated monitoring and control systems that optimise the performance of vessel sub-systems can deliver substantial fuel savings. Short payback.	<10%	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Table 8.6 ▶ Operational strategies

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Fuel additives ● ● ● ●	Fuel additives that reduce soot build-up in exhaust systems can have a positive impact on fuel efficiency. Medium payback.	<2%			<input type="checkbox"/>
Port turn-around time ● ● ● ● ●	Design features such as ramps and alongside hold access, together with port-side improvements such as more efficient gantry cranes, can enable slower speeds at sea for vessels operating on fixed schedules. Short payback.	<10%	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Propeller surface maintenance ● ● ● ● ●	Wet cleaning and polishing propeller surfaces to reduce roughness and the accretion of organic materials can significantly reduce propeller resistance and improve fuel efficiency. This can be accomplished without removing the vessel from its commercial duties.	<10%			<input type="checkbox"/>
Hull coating ● ● ● ● ●	Hardened, low-resistance hull coatings reduce frictional resistance and can reduce fouling. Short payback.	<5%	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Table 8.6 ▶ **Operational strategies** (continued)

Strategy ● Tanker/bulker ● Container ● Ro-Ro ● Ferry-cruise ● Offshore supply	Description	Fuel efficiency gain	New build	Retro-fit	Operational
Hull cleaning ● ● ● ● ●	Frequent hull cleaning can lead to improved fuel consumption. Short payback.	<3%			<input type="checkbox"/>
Ship speed reduction ● ● ● ● ●	Reducing ship speed is one of the most effective ways of reducing fuel use and CO ₂ emissions. Short payback. But ship speeds are subject to duty cycle constraints.	<23%			<input type="checkbox"/>
Voyage planning and weather routing ● ● ● ● ●	The shortest distance between two points is not necessarily the fastest or the most fuel efficient, depending on prevailing currents, and weather patterns. Modern weather and sea condition monitoring systems combined with navigational computers allow for fuel efficient routing based on real-time weather and sea conditions. Short payback.	<10%			<input type="checkbox"/>
Optimised vessel trim ● ● ● ● ●	Optimising vessel trim for a given draught and speed can enhance fuel efficiency.	<5%			<input type="checkbox"/>
Optimised autopilot ● ● ● ● ●	Automatic navigation systems can trigger frequent changes in rudder position to account for wind, currents and ship yawing. Advanced adaptive auto-pilot systems reduce unnecessary course changes and thus reduce overall travel distance and corresponding fuel use.	<4%		<input type="checkbox"/>	<input type="checkbox"/>
Overall energy awareness ● ● ● ● ●	Company incentives for fuel-efficient operations, especially when integrated into crew management responsibilities, can ensure that fuel efficiency is integrated into daily vessel operations.	<10%			<input type="checkbox"/>
Condition-based maintenance ● ● ● ● ●	Ensuring that hull, propulsion and engine systems are all maintained at high levels of fuel efficiency performance can be greatly facilitated by real-time monitoring of sub-system performance and condition-based, rather than schedule-based, maintenance.	<5%		<input type="checkbox"/>	<input type="checkbox"/>

Overall fuel efficiency potential from technical and operational strategies

Taking these options together, the overall potential for CO₂ emission reductions from improved new build vessel designs is estimated to be up to 30%. Technical retrofit and maintenance strategies can potentially reduce CO₂ emissions from the existing fleet by up to 20%. Operational improvements could potentially reduce fuel use and CO₂ emissions, on average, by as much as 40% (consistent with Hobson, *et al.*, 2007). Combining technical and operational measures, it might

be feasible to reduce CO₂ emissions by up to 40% per tkm by 2030 and by up to 60% per tkm by 2050. These projections are consistent with aggregate estimates made by Berrefjord *et al.*, 2008, and slightly higher than those reported in Energy Technology Perspectives 2008, ETP 2008 (IEA, 2008b).

In practice, ships are designed and operated according to many criteria, of which fuel savings and CO₂ emissions are only a small part. Factors such as the need to react quickly to market opportunities for new vessels, capital constraints, duty cycles and environmental awareness can all limit the priority given to fuel efficiency technologies and operational practices. More research is needed to better understand what is likely to happen to fuel consumption in different circumstances, such as different fuel and CO₂ prices. More specific cost estimates for each measure are also needed. The full potentials estimated here are unlikely to be reached without very high oil or carbon prices, or strong policy measures. Some policy options are discussed later in the chapter.

The relationship between owners and operators is also an important factor in securing the maximum potential savings in fuel consumption. This is especially complicated in maritime transport where ships, especially bulk carriers and some tank and container vessels, are often hired under several successive charter party agreements, where fuel costs may be borne by the owner, the vessel operator or the cargo owner, and where the ownership of the cargo and responsibility for fuel costs may change while the vessel is under way. The reality is that, except where vessels are built and designed for owner-operators, the lack of direct responsibility for ship fuel costs means that the potential fuel economy is not maximised in many new builds. Similar issues arise in attempting to realise the full potential for operational fuel savings and CO₂ reductions in that responsibility for en-route fuel consumption may be distributed between several parties, such as the vessel owner, the vessel operator, the crew manager and the cargo owner, none of whom has effective responsibility for reducing fuel consumption.

Despite these challenges, vessel owners and operators have been responsive to energy prices and have sought ways to improve, to some extent, the overall energy efficiency of new builds and to reduce the energy consumption of existing vessels through operational changes and technology retrofits. One of the most effective adjustments that vessel operators can make to rapidly reduce fuel consumption is to reduce speeds. In the early 1970s, the maritime sector responded to rapidly increasing oil prices first by reducing overall speeds and later by exploiting economies of scale through the specification of larger vessels, some of which then rapidly became uneconomic as oil prices fell. The rapid spike in oil prices in the first half of 2008 also saw many vessel operators return to speed reductions, especially for relatively high-speed container services. In some cases, the fuel savings from speed reductions can more than offset the costs of adding an additional vessel to maintain schedule frequencies and capacities.

Travelling at slow speed does not necessarily minimise fuel consumption when other relevant factors are considered (Box 8.3). But there is evidence of a gap between optimum travel speeds and actual speeds. One small survey revealed that fuel consumption can be as much as 26% higher than optimum fuel consumption, largely due to differences in travel speed. The close monitoring of fuel consumption against the optimum level, and adjusting travel speed and other factors accordingly,

can reduce this gap to around 4% with most of the remaining gap due to port-side cargo operations and delays (Bond, 2008).

In practice, commercial and operational imperatives often prove more important than reducing fuel costs and CO₂ emissions. Vessels carrying high-value cargoes, for which levels of reward are linked to time-sensitive delivery schedules are unlikely to reduce speeds. Overall vessel or service costs, including operating and port costs, may also affect speed decisions. For example, slower steaming may entail night-time or week-end port arrivals when container handling costs may (in some ports) be much higher than during regular port hours. Avoiding port congestion may also require faster or slower steaming.

Costs of CO₂ reduction

To date, most of the measures outlined above have not been subjected to a systematic cost analysis. However, IMO (2009) provides some cost estimates based on analysis of a subset of the universe of potential measures, focused on retrofit options for existing ships. It estimates CO₂ abatement costs for about 25 near-term measures, using a societal discount rate and a range of uncertainty in cost estimates. The value of fuel savings are taken into account. The result is a cost curve for a subset of available measures that has from 210 Mt CO₂ to 440 Mt CO₂ reduction at a marginal cost of less than USD 150 per tonne, and with most measures available at net negative cost, *i.e.* net savings to the operator, at least given the low discount rate (which implies taking into account more years of fuel savings than many operators may actually do).

The report does not give any details on the particular measures, and represents just an initial step toward much more thorough costing efforts, but it suggests that there may be a wide range of measures available at low cost. Further, since the report was restricted to near-term retrofit options, it may use cost assumptions that are higher at present than they will be in the future – to the extent that costs decline as technologies are improved, production scales increased, etc.

Box 8.3 ► **Costs and marginal CO₂ abatement from speed reductions for container vessels**

Oceanic transport services are optimised to provide fixed and dependable service schedules to shippers. Container vessels are fast but relatively fuel inefficient. Speed reductions can, therefore, impact significantly on fuel consumption. But when speed reductions affect service frequency and quality, operators may lose out to competitors. In addition, as voyages take longer, operators may face additional fixed daily costs, e.g. on crew payments.

The table below, based on a simple container service cost model, explores the cost impacts of speed reduction in the face of increased fuel costs. In this case, an increase in bunker fuel costs – from USD 300 to USD 550 per tonne – leads to additional annual fuel costs of USD 66 million. An operator reducing speed by around 20% and adding an extra vessel in the service string in order to maintain capacity and the level of service would potentially save USD 31 million despite added ship-related costs. This simplified model is consistent with observed behaviour among major liner service providers during the fuel price spike experienced during the summer of 2008.

Table 8.7 ▶ Comparison of yearly container service costs

	Normal speed 5 ships, USD 300/t fuel	Normal speed 5 ships, USD 550/t fuel	Slow speed 6 ships, USD 550/t fuel
Speed (knots)	24.2	24.2	19.1
Voyage duration (days)	38.1	38.1	44.5
Voyages per ship per year	9.6	9.6	8.2
Required number of ships for service string	5.4	5.4	6.4
Total bunker costs (USD million per year)	80	147	104
Total service costs (USD million per year)	182	248	217

Notes: Assumes 8 500 twenty-foot equivalent unit (TEU) capacity vessel, 14 000 nautical mile service schedule, weekly frequency, seven port calls per voyage. Excludes terminal, inland handling and container costs.

Source: calculations based on Stopford (2009).

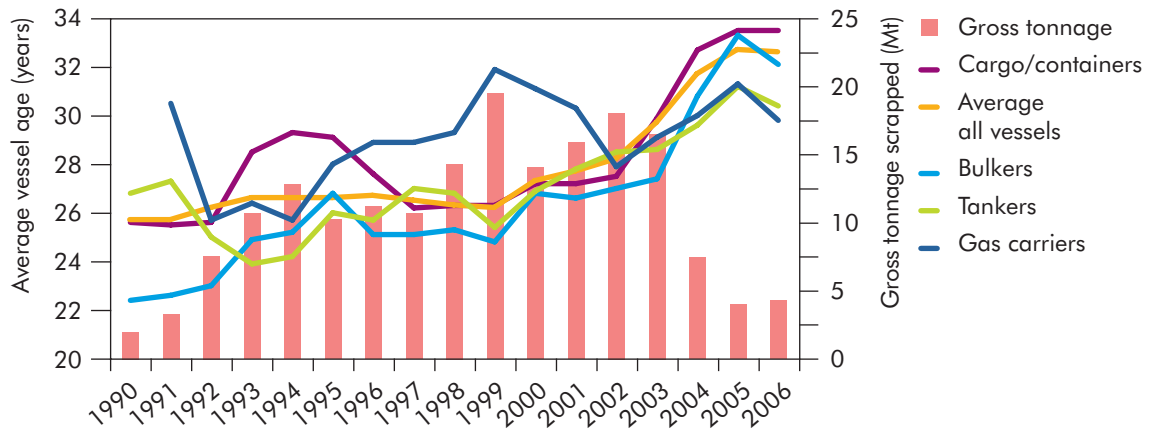
Another study has looked at the potential aggregate impacts of speed reductions for liner shipping to and from the United States (Corbett, Wang and Winebrake, 2009). This examines potential fuel savings and CO₂ emission reductions in two scenarios: first where vessels slow down and service frequency falls, and second where vessels slow down and ships are added to retain service frequency. Fuel-related CO₂ reductions in the first scenario are about twice those in the second scenario. It is estimated that, at a fuel price of USD 300/t, a 10% reduction in speed results in a marginal CO₂ abatement cost of around USD 20/t and a 25% reduction in speed results in a marginal CO₂ abatement cost of USD 50/t (Wang, 2009).

Ship replacement and fleet turnover

Ships represent a considerable capital investment and have long commercial lives. In 2006, the average age of vessels being withdrawn from commercial service for recycling was approximately 32 years, up from approximately 27 years in the early 1990s (Figure 8.9). Only a small share of the current shipping fleet will be replaced in the next five to ten years and many new vessels are already on order. In December 2008, approximately 1 400 container vessels were on shipyard order books, accounting for a total capacity of over 6 million twenty-foot equivalent units (TEUs), with slightly more than half of this capacity accounted for by large (over 8 000 TEU) vessels (CI Online, 2008). This means that operational and maintenance-related measures are likely to be the major source of any efficiency gains in the near to medium term, with new vessel and propulsion technology-related gains playing an increasingly important role after 2020. By 2050, virtually the entire fleet of ocean vessels will be replaced.

Rapid deterioration of the economic climate in late 2008 has led to a sharp decrease in container traffic and an oversupply of capacity on most container trades. This has led vessel owners to withdraw vessels from commercial service

Figure 8.9 ▶ Average age and gross tonnage of vessels withdrawn from commercial service



Source: Mikelis, 2007.

Key point

Maritime vessels can remain in operation for 30 or more years. The average age of vessels has risen significantly in recent years.

and to accelerate the scrapping of older ships. Depressed GDP growth forecasts and tight credit markets mean that relatively fewer ships will be ordered over the next few years. This will further slow the penetration of the most recent fuel-saving designs and technologies. For bulk traders and tankers, a precipitously steep drop of 97% in charter-party rates from July 2008 to December 2008 has effectively removed much of the near-term incentive for ordering new vessels, again slowing the penetration of fuel-saving designs and technologies.

Fuels for maritime shipping

Revisions to MARPOL Annex VI, which deals with air pollution from ships, are expected to result in alternatives to traditional HFO increasingly being used in the shipping sector. It is unlikely, however, that these new requirements will trigger the greater use of low-carbon fuels. As discussed in Box 8.2, some low-sulphur alternative fuels may actually increase overall life-cycle GHG emissions.

The typical large, slow-speed, two-stroke engines on most ships can handle a wide range of fuels, including HFO, raw vegetable oils, waste oil and tallow, as long as they conform to specific acidity, viscosity and performance characteristics. Biofuels could be used in the maritime sector and uptake is likely to depend mainly on fuel prices. Fuels such as biodiesel derived from oil seed may also be used. Biocrude, the low quality of which makes it poorly suited to other uses, can be used in slow-speed marine engines and could potentially be processed using local biomass near ports. More work is needed to assess the viability and cost of this option, and the potential contribution it could make (Opdal and Hojem, 2007).

Although engines are largely compatible with biofuels, existing HFO-based fuel systems will require some modification or different operational procedures to avoid precipitate formation and the clogging of components. Pure vegetable oils and biocrude can also lead to problems in fuel-injection pumps (Opdal and Hojem, 2007; Opdal, 2008).

With oil prices under USD 100/bbl, biofuels are likely to remain more expensive than petroleum fuels. HFO is one of the least-expensive petroleum fuels. Ship operators may face little economic incentive to switch to low-CO₂ fuels without significantly higher oil prices or high carbon prices. The IMO concludes that, without policy intervention, around 5% to 10% of all fuel used will be switched to LNG in 2020. By 2050, 25% to 50% of coastal vessel fuel and 10% to 20% of ocean-going crude oil tanker fuel is expected to be LNG and up to 20% of all ships are expected to switch to synthetic, probably coal-based, diesel (Buhaug *et al.*, 2008).

The IEA Baseline scenario assumes that the vast majority of future shipping fuel will be HFO or marine diesel. The BLUE Map scenario assumes that policy support enables low-GHG biofuels to achieve a 30% market share by 2050. These could be either advanced BTL biodiesel or some form of probably much cheaper biocrude.

International GHG reduction policies for maritime transport

The international maritime sector has no quantified GHG emission reduction targets under the Kyoto Protocol. In the absence of an agreed formula for allocating responsibility for emissions among nations, burden-sharing efforts cannot be allocated. The IMO has been tasked with elaborating GHG emission reduction strategies. A proposal is expected to be presented to the UNFCCC COP 15 in December 2009, which will provide a framework for including international maritime emissions within a successor treaty to the Kyoto Protocol.

One issue that has emerged within the IMO discussions is that any global shipping GHG-reduction plan is likely to require nations that currently have no GHG-reduction targets under the Kyoto Protocol to accept targets for the fleet of vessels under their registry. These nations fear that this approach might establish an unwelcome precedent for the overall climate change negotiations, in which the principle of “common but differentiated responsibilities” has been accepted. More than two-thirds of the world’s international maritime fleet is registered in countries that have no defined GHG-reduction targets (Figure 8.10). In terms of ownership, however, this pattern is reversed with about two-thirds of the world’s fleet being owned by nationals of countries that do have GHG-reduction targets. Similarly, two-thirds of vessel operators are nationals of countries with targets.

At present, the IMO is considering several instruments that might comprise its contribution to the post-Kyoto climate regime. These are outlined in the following section.

Figure 8.10 ▶ World fleet by flag and nationality of owner and operator, 1978-2007

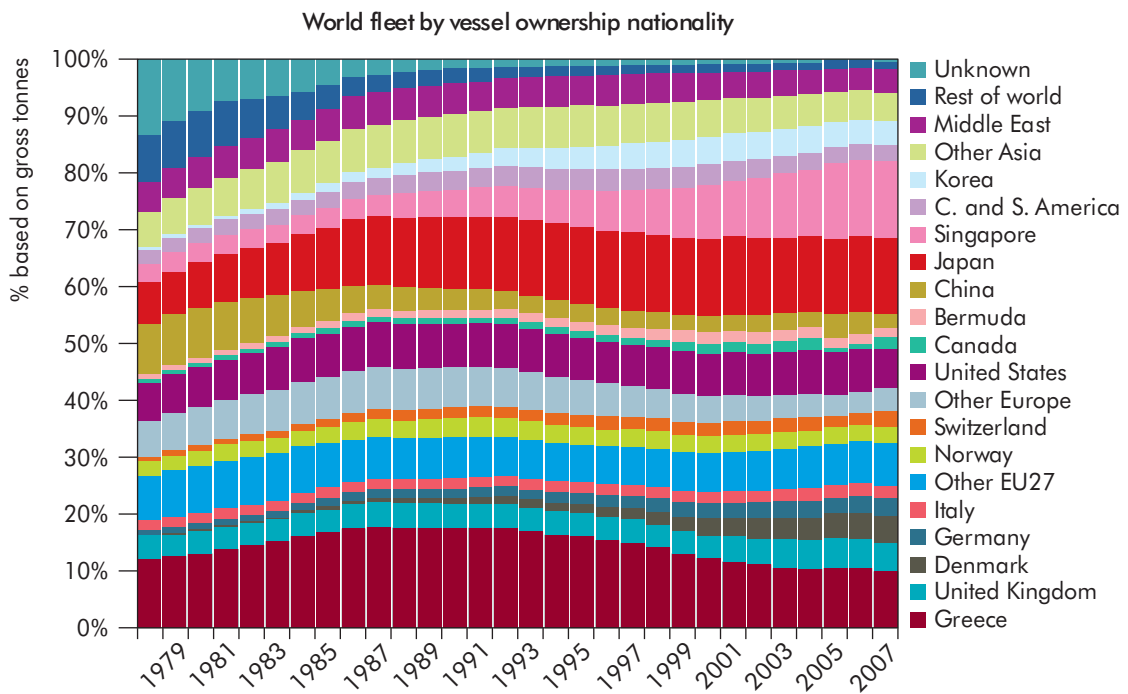
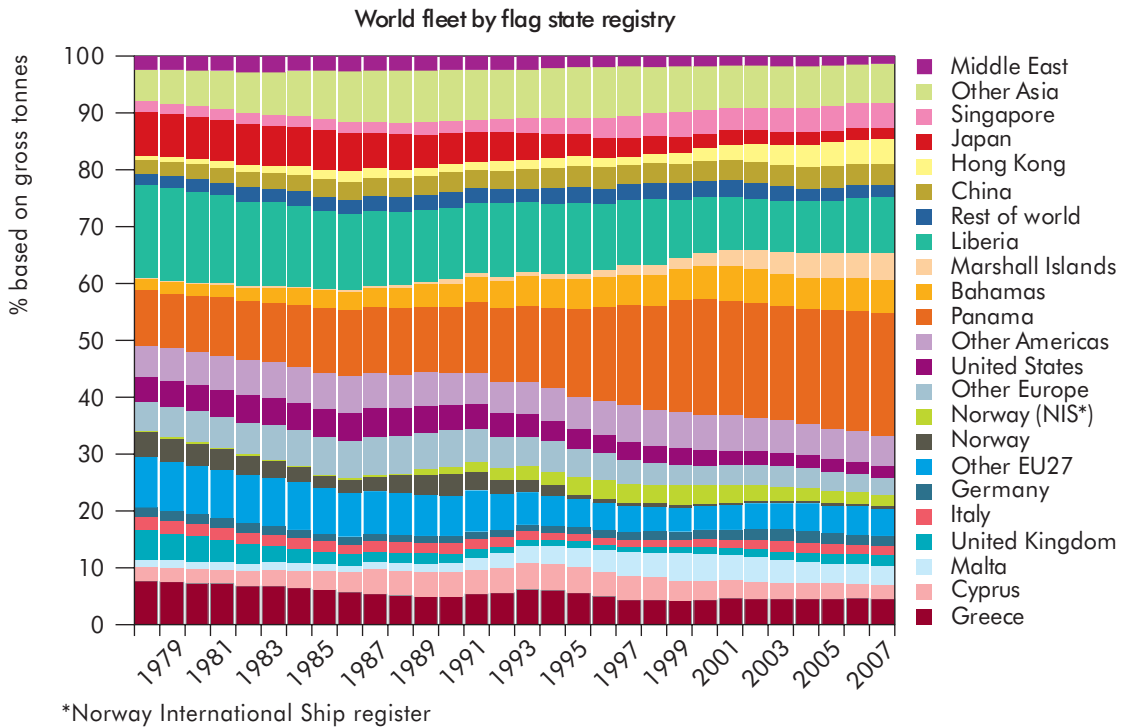
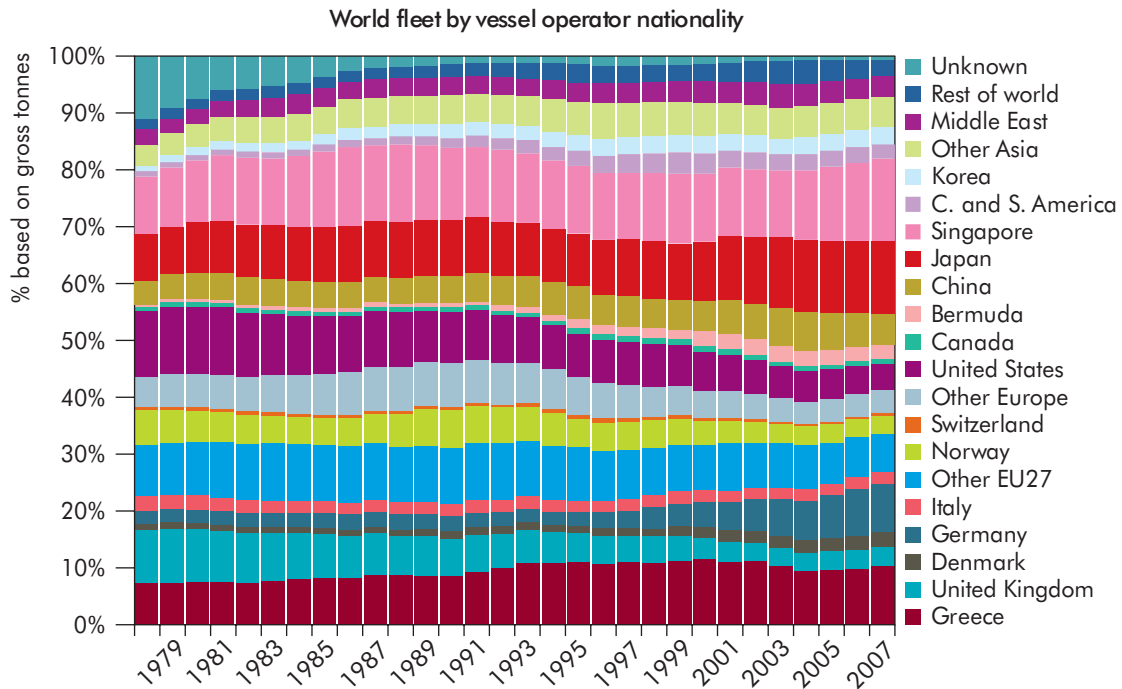


Figure 8.10 ▶ **World fleet by flag and nationality of owner and operator, 1978-2007** (continued)



Source: Lloyd's List Optimar, 2009.

Key point

Countries of ship registry, ownership and operator vary significantly, complicating policy-making efforts.

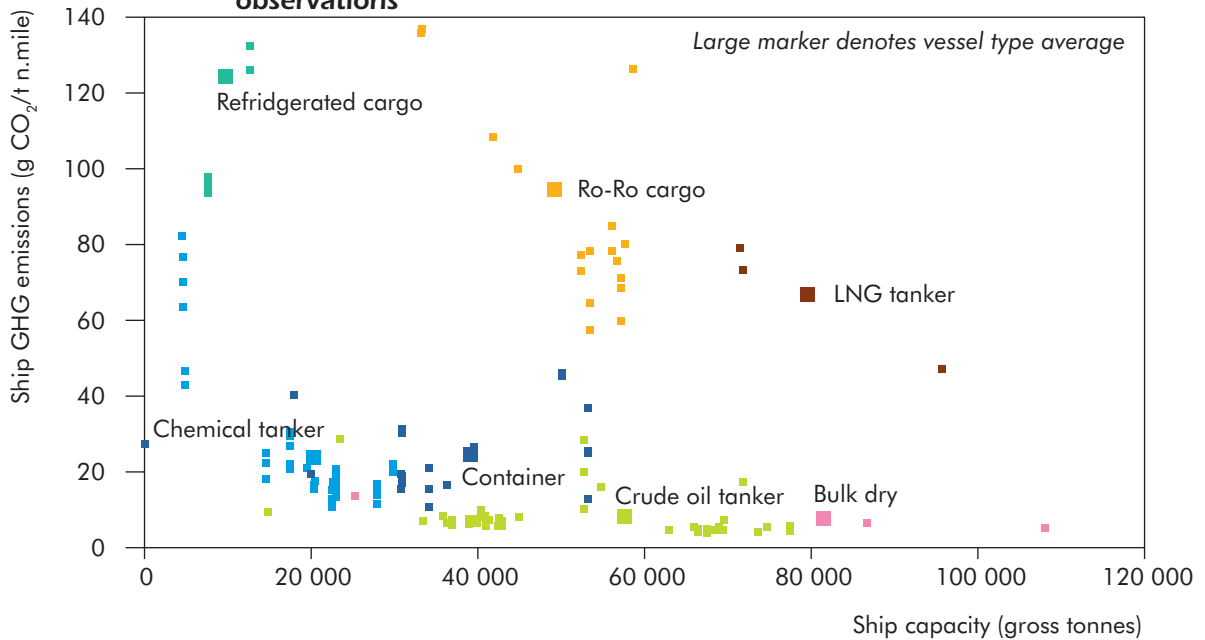
IMO CO₂ design index

One option under consideration is the creation of a mandatory CO₂ design index for new vessels. This would specify a minimum design standard in terms of energy efficiency –and a maximum design standard in terms of CO₂ emissions– for each vessel type. It would essentially be analogous to the road vehicle fuel efficiency standards in force in a number of countries. The design index would allow comparisons to be made of the CO₂ emissions of similar vessels, and would set a minimum benchmark that could be periodically revisited in order to reduce overall maritime CO₂ emissions over time.

Initial trials of an early form of the IMO CO₂ design index show that the energy consumption of similar sized vessels varies significantly (Figure 8.11). Vessel design is not the only source of variation. Other factors such as cargo requirements and loading, speed, length of empty (ballast) return or repositioning trips, ship condition and maintenance, as well as weather and currents, will all either have to be normalised or otherwise accounted for in any index (Buhaug, 2008).

Given the reluctance of some countries to deviate from the CO₂ mitigation principle of common but differentiated responsibilities, the possible mandatory nature of

Figure 8.11 ▶ CO₂ index and gross tonnage for ship groups, average and individual observations



Source: ITF, adapted from Buhaug, 2008.

Key point

Average CO₂ emissions intensity can vary substantially for similar ship sizes and types.

the CO₂ design index has led to considerable resistance. But narrowing the reach of the proposed index by making it mandatory only for Annex 1 countries would considerably weaken the instrument, as over two-thirds of the world's registered fleet would no longer come within its scope.

Other difficulties facing the adoption of a CO₂ design index are related to its coverage and metrics. To be fully effective, for example, it would need to take account of auxiliary power requirements and of different vessel duty cycles. At present, it is not clear what form the final CO₂ design index might have, or whether, or not it will become a mandatory or voluntary instrument for non-Annex 1 countries.

Voluntary CO₂ operational index and other measures

Although a CO₂ design index shows some promise as a way to reduce CO₂ emissions from new vessels, it would do nothing to reduce emissions from vessels currently in operation. It would, therefore, only have a noticeable impact over the medium to long term.

To address emissions from existing vessels, the IMO is in the process of updating a set of best-practice measures for operational fuel savings and CO₂ emission reductions. This index would allow vessel owners, operators, shippers and administrations to benchmark individual vessels and company performance. While some national administrations might make the operational index mandatory for

their flagged vessels, it is unlikely to be adopted by the majority of the world's flag states and, as such, will probably only have a relatively limited impact. Even so, it could provide a means for administrations to differentiate between vessels, e.g. through port fees, CO₂ fee rebates or other incentive-based instruments, according to their emission profiles.

International measures

Initial discussions are also under way within the IMO on economic and market-based instruments such as a global fuel levy or the inclusion of maritime CO₂ emissions within a cap-and-trade system. Many countries have made it clear that they are unwilling to take on a requirement to reduce GHGs in these ways. While a global levy might be procedurally more simple to put into effect, its administration and determining how its proceeds should be allocated are daunting challenges. Lessons from the redistribution of other transport taxes and levies would argue for any revenues to be applied directly to the further reduction of CO₂ emissions and energy use in the maritime sector.

Including maritime emissions within a cap-and-trade system would also face considerable difficulties. But including maritime emissions within a broader cross-sectoral trading system might allow for an influx of money to the sector if lessons on the marginal abatement costs of other pollutants from maritime activity hold true for CO₂ emissions.¹⁰ If and when existing and planned trading schemes in the European Union, Australia, California, Western United States, British Columbia and New Zealand were to allow for cross-trading, then an international framework might exist also to support the inclusion of maritime emissions. But even then, securing agreement on the method for allocating emissions to flag states, or to vessel owners or to vessel operators, whether by auctioning or grandfathering or some other means, is likely to prove challenging.

Regional and national measures

The maritime sector is a global industry. But, given the obstacles within the IMO to achieving a global approach to the control of CO₂ emissions from the sector, several countries and country groupings are considering unilateral or multilateral action. The European Union has indicated that unless it is satisfied with progress on reducing CO₂ emissions within the IMO, it will unilaterally act to include maritime CO₂ emissions from vessels travelling to and from its ports within the EU Emissions Trading System. The European Union has already done this in respect of international aviation emissions.

Another option for regional action would be for countries to impose CO₂ differentiated harbour dues or to implement some form of CO₂-based emission charge, possibly with some rebating, to favour low-emitting vessels and operators. An IMO CO₂ design index and a voluntary CO₂ operational index could serve as the basis for differentiation.

10. For instance, the marginal abatement costs of NO_x emissions have been shown to be considerably less from maritime sources than from land-based sources – principally because the latter have been increasingly regulated while the former have not. Similar low-CO₂ abatement costs may exist for maritime emissions when compared to more regulated land-side emissions.

Annex

A **MOBILITY MODEL
DOCUMENTATION****Background**
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This Annex describes the IEA ETP Mobility Model (MoMo) in brief form. A more detailed description, along with information on data sources and other related information, is available on the IEA web site (<http://www.iea.org>).

MoMo is a technical-economic model designed to track energy needs and emissions from worldwide mobility, using an accounting framework to link travel, vehicle stocks, efficiency and fuel use. It also takes into account the costs of vehicles and fuels, and related materials and resources.

Currently, MoMo is based primarily on a descriptive approach, allowing the user to create “what-if” scenarios to evaluate the effects of different trends on various outputs. The user can, for example, change the projected number of vehicles sold to affect vehicle ownership in the future, and then check how this change affects fuel demand, all else being held equal. This approach allows the user of MoMo to develop any type of scenario, regardless of past trends. Given the abovementioned characteristics, MoMo can be rated as a simulation model rather than an optimisation model.

In the most recent version of MoMo, a number of key elasticities have been introduced. This addition gives the opportunity to the user to rely on some endogenous relationships, limiting the external intervention to the action on the parameters that define them (*i.e.* GDP per capita and the oil price).

Currently, elasticities have been introduced for vehicle travel (which is linked to fuel prices and personal income) and vehicle ownership (which is linked by an ownership function to the value of personal income).

The introduction of elasticities allows users to estimate the impact of changes in fuel prices, policy variables such as taxes, and economic and demographic variables such as GDP and population.

This approach is now beginning to offer more opportunities to conduct analyses that have an increased level of complexity, to assess which result would correspond to a given price signal, for example.

A**Model fundamentals**
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The calculation of energy consumption and gaseous emissions performed in MoMo is based on the ASIF methodology (Schipper, 2000), adapting some of its aspects in order to fit with the available data for each region considered.

The original ASIF equation is as follows:

$$G = \sum_{\text{modes}} \sum_{\text{fuels}} A_{m,f} S_{m,f} I_{m,f} F_{m,f} \quad (1)$$

in which:

- G is the total emissions of greenhouse gases.
- A represents an activity variable (e.g. vehicle travel).
- S is the structure variable (e.g. the number of vehicles in a given mode).
- I measures energy intensity (e.g. the average consumption of energy of a vehicle).
- F is the GHG emission factor per unit energy consumed.

In the case of transport, the equation (1) can be re-written as follows, for each mode, and then eventually summed for all modes:

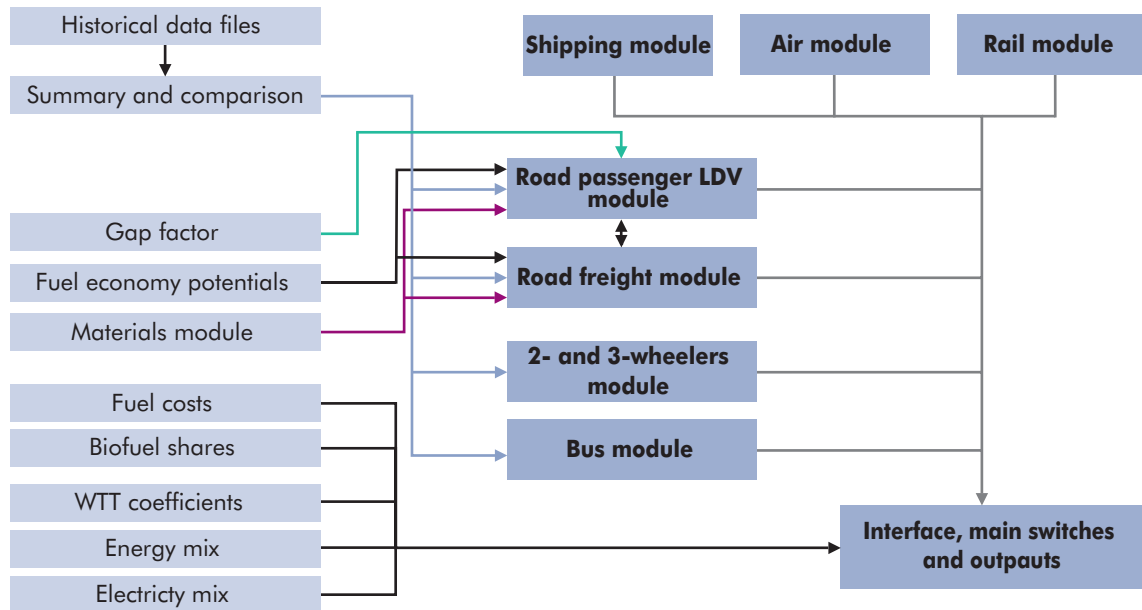
$$\begin{aligned} (\text{GHG emissions})_{\text{mode}} &= \sum_{\substack{i = \text{fuel} \\ j = \text{immatriculation year} \\ k = \text{vehicle class} \\ l = \text{load factor}}} A_{i,j} S_{i,j,k,l} I_{i,j,k,l} F_{i,j,k} \\ &= \sum_{\substack{i = \text{fuel} \\ j = \text{immatriculation year} \\ k = \text{vehicle class} \\ l = \text{load factor}}} (\text{average travel})_{i,j} (\text{vehicle})_{i,j} (\text{specific consumption})_{i,j,k,l} (\text{emission factor})_{i,j,k} \end{aligned} \quad (2)$$

The same equation can be simplified and approximated, using average values for a given mode rather than summing for each vehicle or each vehicle class. This is the approach followed in MoMo. The same methodology is also applied for energy use. F in this case equals a unit factor. A similar methodology allows the calculation for all pollutant emissions but lead. In the case of pollutants, the emission factors multiply directly the vehicle travel, since they are expressed in terms of units of pollutant emissions per km. Lead emissions are estimated multiplying the lead content of a given unit of fuel (essentially leaded gasoline) and the total amount consumed.

Model architecture

To ease the manipulation and implementation of the modelling process, the model is split into several modules that can be updated independently. The main modules correspond to one transport mode, to reflect the different technology / fuel characteristics of each mode.

Figure A.1 shows how the model is organised to allow the user to browse through the model as conveniently as possible.

Figure A.1. ▶ File structure of the IEA Mobility Model

As an example of one module framework, the following text describes the methodology adopted to perform the calculation within the passenger LDV module. A similar approach has been used for road freight modes. In these cases, a stock model helps define some parameters relative to the total vehicle stock on the basis of the characteristics of new vehicles. Other modes have been approached in a similar manner, but with less detail and without the use of a stock model.

Passenger LDVs

Passenger LDV sales and stock data have been gathered for all countries,¹ as well as a large amount of information on vehicle travel, age and fuel economies (all these data are constantly being collected, in order to maintain the basic MoMo databases up to date). The information on the number of vehicles circulating and their average travel allows the calculation of the total amount of vehicle travel.

The ASIF-based equation used within MoMo for passenger transport on LDVs is:

$$\begin{aligned}
 (\text{GHG emissions})_{\text{mode}} &= \sum_{i = \text{fuel type}} \text{ASIF}_i = \\
 &= \sum_{i = \text{fuel type}} \left(\frac{\text{travel}}{\text{vehicle}} \right) (\text{vehicle stock}) (\text{consumption}) (\text{emission factor}), \quad (3)
 \end{aligned}$$

1. These data have a good quality in most countries studied, even if important issues remain (e.g. differences in international classifications, discrepancies amongst different data sources).

in which:

- A is the use of the vehicle, in kilometre per vehicle per year.
- S represents the number of vehicles circulating.
- I measures energy intensity in energy per vkm for each mode and fuel type. In case of liquid fuel, this is the fuel economy, expressed in terms of energy consumption per km.
- F is the GHG emission factor of the fuel.

The same equation is used to calculate total energy consumption. In this case, however, the factor E is not required. The total passenger travel on LDVs can be calculated with a similar approach, excluding the specific consumption of vehicles. The total pkm travelled from the combination of information on the average vehicle load factor and the total vehicle travel.

For the LDV modes in passenger transport, the model allows not only the evaluation of energy consumption and GHG emissions, but also the calculation of pollutant emissions (on the basis of vehicle travel and pollutant emission factors), as well as vehicle and fuel costs on the basis of various vehicle technologies and fuel types. The model can also calculate the requirement of different types of materials for the vehicle fleet, the energy required to produce them, and emissions due to their manufacturing.

Table A.1 shows the modes, vehicle technologies, fuels and key variables contained in the LDV section of the MoMo model.

Table A.1. ► Sectors, fuels and data contained in the passenger LDV module

Travel modes	Vehicle technologies/fuels	Variables
<ul style="list-style-type: none"> • Passenger light-duty vehicles (cars, mini-vans, SUVs): Passenger cars Light trucks 	<ul style="list-style-type: none"> • Internal combustion engine: <ul style="list-style-type: none"> Gasoline Diesel LPG-CNG Ethanol Biodiesel CTL, GTL Hydrogen • Hybrid-electric ICE (same fuels) • Plug-in hybrids (same fuels, with electricity) • Electric vehicle (dedicated EV, electricity only) • Fuel-cell vehicle (hydrogen) The feedstock differentiation for biofuels, electricity and hydrogen is also taken into account 	<ul style="list-style-type: none"> • Passenger kilometres of travel • Vehicle sales • Vehicle stocks • Average vehicle fuel-efficiency (new and stock) • Vehicle travel • Load factor • Fuel use • CO₂ emissions <ul style="list-style-type: none"> Well-to-tank Tank-to-wheel From vehicle manufacturing • Pollutant emissions (PM, NO_x, HC, CO, Pb) • Safety (road fatalities and injuries) • Material demand (e.g. aluminum, platinum)

The regional aggregation system used in the LDV section of the MoMo model is shown in Table A.2. Countries individually tracked in the model are explicitly shown. Currently, this is the case for nine OECD and five non-OECD countries. Other countries are incorporated into the relevant regional aggregations.

Table A.2. ► MoMo regional aggregation system

MoMo geographical aggregation			
OECD regions		Non-OECD regions	
Zone	Region	Zone	Region
OECD North America	Canada	Former Soviet Union	Russia
	Mexico		Asian Transition Economies
	USA		Eastern Europe
OECD Europe	France	China	China
	Germany	Other Asia	Other Asia
	Italy	India	India
	United Kingdom	Middle East	Middle East
	Other OECD Europe		Brazil
OECD Pacific	Australia and New Zealand	Latin America	Other Latin America
	Japan	Africa	South Africa
	Korea		Other Africa

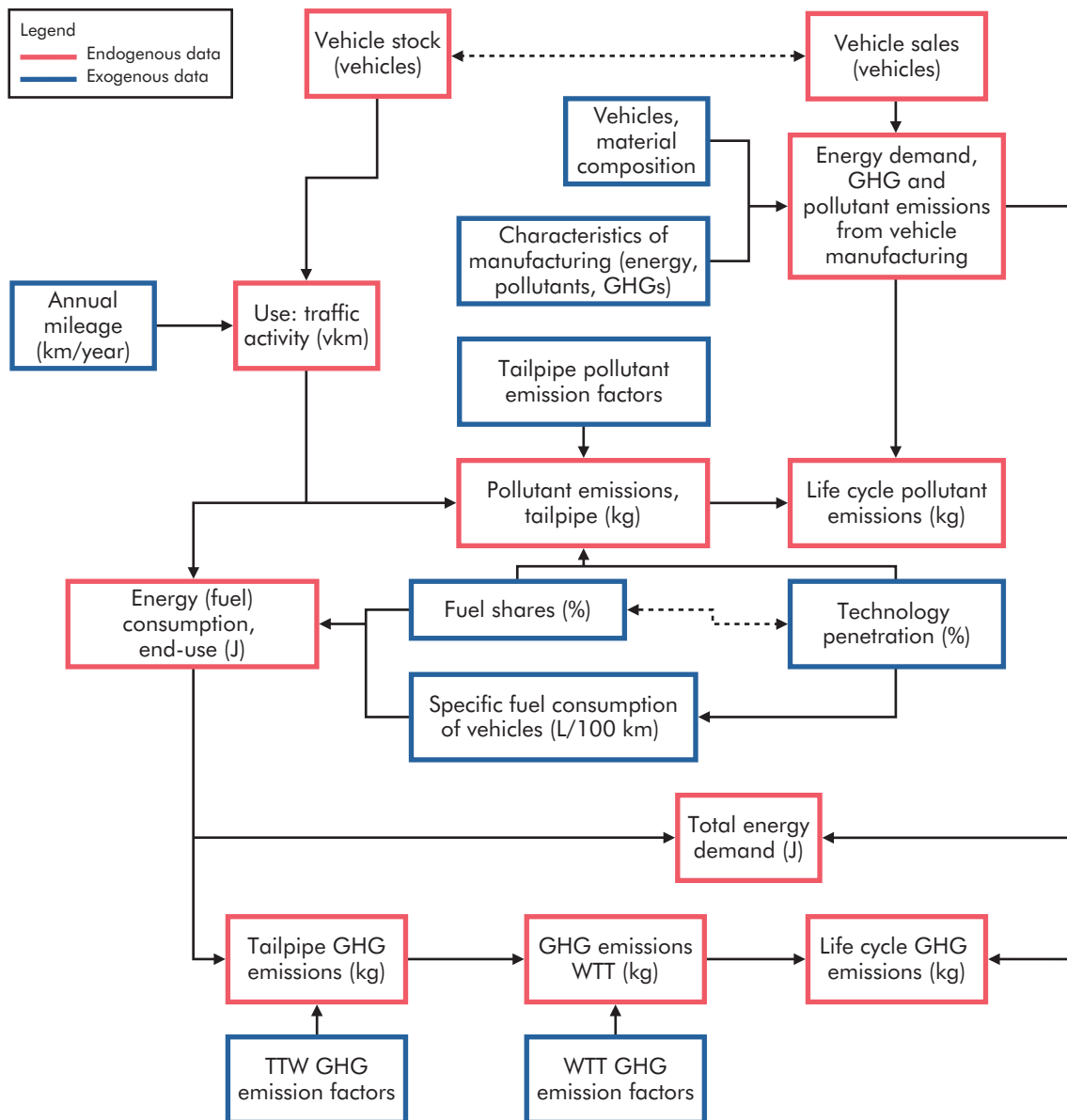
Although the ASIF methodology is straightforward and transparent, it needs a reasonable amount of simple data; many countries do not yet gather the type of data needed. The IEA ETP staff and its partners developed a database to fully elaborate the data needed to cover all the variables for all regions in the model. The development of this database represents an on-going activity, and the model is updated on a regular basis with the most recent information collected.²

A simplified flow diagram of the model structure can be found in Figure A.2. The diagram gives an idea of the basic interconnections amongst the variables and the data contained in the model.

The blue boxes in Figure A.2 represent exogenous inputs into the model. For past years, these data are taken from the IEA MoMo statistical database and include official IEA data (such as fuel consumption estimates) and unofficial data collected by the MoMo team from various sources, including national databases and private data sources. For future years (projections), the data come either from exogenous input or from functions of other variables, controlled with basic parameters by the user.

The data in red boxes are calculated internally in the model. In the case of historical data, most results are checked against external data sources.

2. To the extent possible, historical data have been gathered from 1970 on a yearly basis. However, it is important to note that the data reliability and availability before 1990 has often a significantly lower quality than data following 1990. For these reasons, data for years before 1990 often required estimations and should be considered with the adequate caution. The data within MoMo are updated as often as possible.

Figure A.2. ▶ Flow diagram for motorised road modes in MoMo

Stock calculation

For prospective years and in the case of passenger LDVs and road freight modes (light commercial vehicles, medium freight trucks and heavy freight trucks), the stock is calculated from the new vehicles sales, the used imports and the average age of the vehicle type. To get the stock, MoMo is summing the new registrations up to the average age of the stock, as shown in (4). The current version of MoMo assumes the used imports have the same life expectancy as new vehicles.

$$\text{Stock} = \sum_{\text{year} = 1}^{\text{avg fleet year}} \text{New registrations} \quad (4)$$

As the model operates with a 5-year step data, a linear interpolation is calculated if the average age of the fleet does not match a model year.

Elasticities

Vehicle ownership is currently evaluated on the basis of the typical S-shaped function of personal income widely described and analysed in literature (e.g. in Dargay and Gately, 2007). Vehicle sales result from the combination of the information on the vehicle stock derived from ownership functions and assumptions on the average vehicle lifetime. Alternatively, exogenous assumptions can target directly vehicle sales and average vehicle lifetimes. In this case, the vehicle stock is evaluated as a result of such assumptions.

When the model is used with the “travel elasticity switch” activated, the variation of the number of km travelled by each LDV (Travel) (and therefore also the total number of vkm run by LDVs) in a given time period (from y to $y+n$) is determined by the initial value of travel per vehicle, the variation of the cost of driving (Cost) and the change of personal income (Income). The mathematical relation used to describe the link amongst these variables is reported here:

$$\frac{\text{Travel}(y+n)}{\text{Travel}(y)} = \left(\frac{\text{Cost}(y+n)}{\text{Cost}(y)} \right)^\alpha \left(\frac{\text{Income}(y+n)}{\text{Income}(y)} \right)^\beta \quad (5)$$

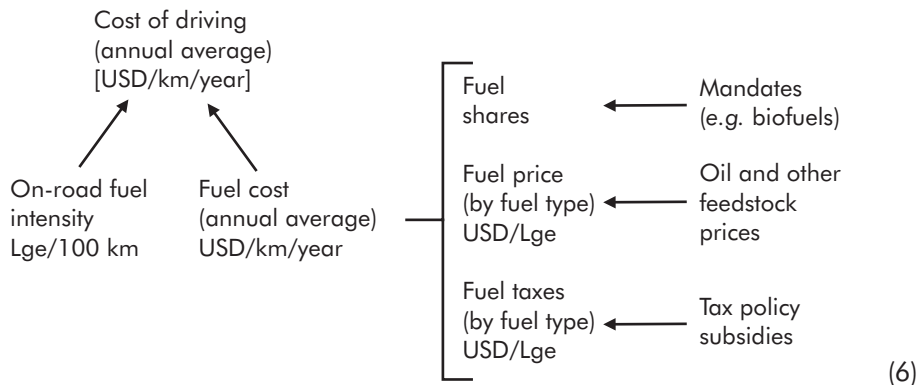
α and β are, respectively, the price and income elasticities required by the model.

The default values proposed in the MoMo model (consistent with the suggestions obtained from the ITF analysis, largely based on US data) are:

- Between -0.2 and -0.3 for the travel elasticity with respect to the variation of the cost of driving (fuel price, USD/L * efficiency, L/km).
- Relatively low (0.01) for the effect of income on travel per vehicle (with a much higher elasticity for income effect on car ownership).

More data and estimation work is needed to improve the estimation of travel elasticities, especially to get appropriate elasticity values for different world regions. Time series data on travel, incomes and fuel prices, and other variables are needed for as many countries as possible.

The cost of driving (Cost), in particular, requires a number of other inputs to be evaluated:

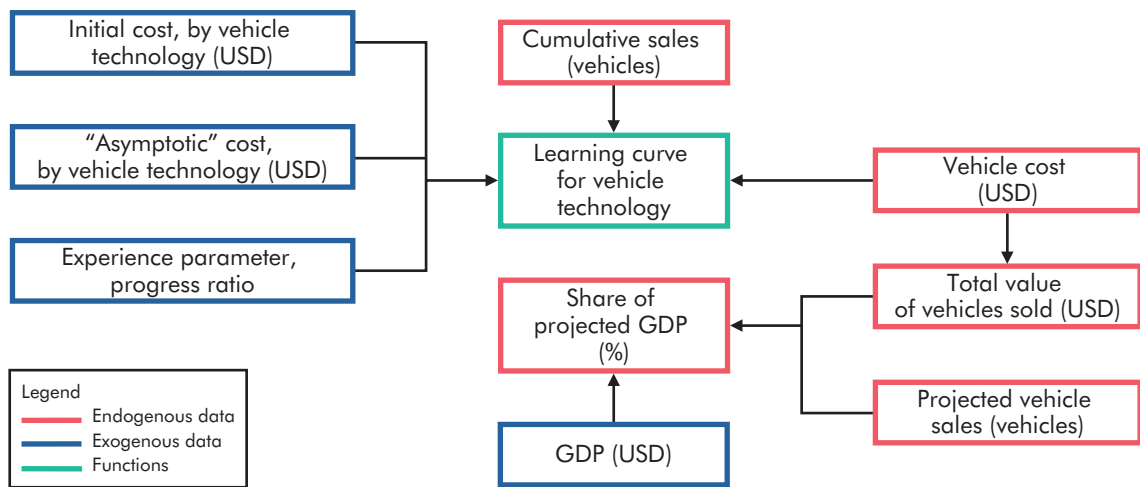


All these input variables need to be evaluated in the model and fed to its elasticity module.

Costs

The model is also used to estimate the average cost of new vehicles entering the market. A specific cost module is used for this purpose, and learning curves have been used to estimate future costs of new vehicle technologies. Figure A.3 shows the basic logic used to determine vehicle costs and the weight of vehicle sales in the estimation of the total GDP in a given region.

Figure A.3. ► Determination of the cost of vehicles



As in (7), the final vehicle cost in given year $VC(y)$ is given by the cost of a standard vehicle built with conventional materials and excluding the powertrain $G(y)$, summed to the cost of all the N powertrain and glider-improving technologies used on the vehicle $TC(y)$, expressed on the basis of the following parameters:

- The cost of the technology (TC_{init_i}) corresponding to the initial market introduction of it (and associated to an initial cumulative production CP_{init_i}).
- The cost of the technology in the far future (e.g. cost of materials required plus markup), or asymptotic cost (TC_{asym_i}) .
- The cumulative production reached for the given technology $(CP(y))$.
- The *experience parameter* ε . This is a value that is evaluated in such a way that the change of the cost is equal to the progress ratio (an input required in the model) per each doubling of the cumulative production for a given technology.

The following mathematical relation describes the link amongst these variables reported above:

$$VC(y) = G(y) + \sum_{i=0}^N TC_{asym_i} + \left(TC_{init_i} - TC_{asym_i} \right) \left(\frac{CP_i(y)}{CP_{init_i}} \right)^{\varepsilon_i} \quad (7)$$

Materials

The amount of materials required for the vehicle manufacturing is also tracked in the model, thanks to the integration of a module first developed at the MIT (Camanoe Associates, 2005). The materials module also allows the estimation of the upstream energy requirements of vehicle manufacturing, as well as the emissions of atmospheric pollutants and GHGs.

The demand for several materials (e.g. steel, aluminium, copper, lithium, platinum-group metals, and plastics, amongst others) is tracked in this module. Specific material requirements, relevant to each of the LDV technologies, are all taken into account.

The evaluation of the energy requirements associated to each material depends on parameters associated to its production process. Such parameters are all exogenous in the model. They include:

- The demand of electricity in the extraction, transport and production process.
- The electricity mix in a given region (*i.e.* the region where the vehicle is sold).
- The demand of primary and secondary energy for the extraction, transport and production process (taking into account the efficiencies of the processes, but excluding electricity).

Each process is also characterised with respect to the emissions of pollutants and fugitive GHGs (such as methane). Each energy source, finally, is associated to its specific GHG emission factor to estimate total GHG emissions.

Emissions (pollutants)

Tailpipe pollutant emissions are evaluated on the basis of the different vehicle regulations enforced in different world regions. Each LDV technology is characterised by the relevant emission factors.

In projected years, vehicles emissions are evaluated on the basis of the characteristics of the vehicle sold in a given time period, taking into account the vehicle sales profile and the expected changes of emission factors.

The majority of the tailpipe pollutant emissions estimates are based on vehicle travel, since emission factors are generally expressed per unit of vehicle travel. In this case, each group of vehicles is associated with the corresponding pollutant emission factors, and each vehicle is assumed to be driven for an amount of km equal to the average travel distance considered in the time period taken into account. As times goes by, older vehicles are progressively scrapped and excluded from the calculation.

The only exception to this rule is lead, since lead emissions are primarily associated to the lead content in the fuel and the total use of fuel containing lead. In this case, the driver for the estimation of lead emission is the amount of leaded fuel used, associated to the relevant lead emission factor (which depends on the composition of the fuel used).

GHG emissions

The GHG emissions for passenger LDVs is divided into three distinct values:

- Well-to-tank GHG emissions, mainly dependent on the fuel pathway and energy carrier characteristics.
- Tank-to-wheel GHG emissions, which depend on the average fuel economy of the vehicles and the characteristics of the fuels they use.
- Emissions associated to the vehicle manufacturing process, which depend on the material composition of the vehicle, the emissions associated to the manufacturing of each material, and the emissions due to the vehicle assembly. All figures are also affected by the electricity mix of the region considered.

Data sources

Intensive data gathering have been pursued for all road motorised modes. Vehicle sales and stock, fuel consumption and travel figures for every region/country available have been placed in relevant files. Information on the main data sources used to characterise each MoMo region can be found on the IEA website (www.iea.org).

Annex

**B ABBREVIATIONS,
ACRONYMS AND UNITS****Abbreviations**

2W	Motorised Two-wheeler
3W	Motorised Three-wheeler
ACA	Airport Carbon Accredited
AHSS	Advanced high-strength steels
AMT	Automated manual transmission
ATM	Air traffic management
BRT	Bus rapid transit
BTL	Biomass-to-liquids
CAFE	Corporate average fuel economy
CCS	Carbon capture and storage
CDA	Continuous descent approach
CFRP	Carbon-fibre reinforced plastic
CH ₄	Methane
CI	Compression ignition (diesel) vehicle
CNG	Compressed natural gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ eq	Carbon dioxide equivalent
CTL	Coal-to-liquids
CTM	Collaborative transportation management
CVRS	Computerised vehicle routing and scheduling
CVT	Continuously variable transmission
DME	Dimethyl ether
ECR	Efficient consumer response
EEA	Energy and environmental analysis

EV	Electric vehicle
FAME	Fatty acid methyl ester
FC	Fuel cell
FCV	Fuel cell vehicle
FML	Fibre metal laminate
FT	Fischer-Tropsch
GDP	Gross domestic product
GHG	Greenhouse gas ¹
GTL	Gas-to-liquids
GVWR	Gross vehicle weight rating
GWP	Greenhouse warming potential
H ₂	Hydrogen
H ₂ O	Water
HC	Hydrocarbons (unburned, typically gaseous)
HDV	Heavy-duty vehicle
HFC	Hydrogen fuel cell
HFO	Heavy fuel oil
HRJ	Hydro-treated renewable jet fuel
HSR	High-speed rail
HSS	High-strength steels
HTU	Hydrothermal upgrading
HVF	Heavy vehicle fee
ICE	Internal combustion engine
ITS	Intelligent transport system
LCA	Life-cycle analysis
LCV	Light commercial vehicle
LDV	Light-duty vehicle
LED	Light-emitting diode
LH ₂	Liquid hydrogen

1. Throughout this study except where noted, greenhouse gases include CO₂ emissions from vehicles, and CO₂, CH₄ and N₂O emissions from fuel production. It does not include other GHGs, such as H₂O from aircraft or SO_x from shipping.

Li-ion	Lithium ion
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LRR	Low rolling resistance (tyres)
LRT	Light rail transit
LT	Light truck
MAC	Mobile air conditioning
MDO	Marine distillate oil
MY	Model year
N ₂ O	Nitrous oxide
NiMH	Nickel-metal hydride
NO _x	Nitrogen oxides
O ₃	Ozone
OBU	On-board unit
OCR	Optical character recognition
PBR	photobioreactors
PC	Passenger car
PEM	Proton exchange membrane
PHEV	Plug-in hybrid electric vehicle
PISI	Port injection spark ignition
PM	Particulate matter
POU	Point of use
PPP	Power purchasing parity
R&D	Research and development
RD&D	Research, development and demonstration
RF	Radiative forcing
RoRo	Roll-on/Roll-off
ROW	Rest of the world
RR	Rolling resistant (tyres)
SAGD	Steam-assisted gravity drainage

SCR	Selective catalytic reduction systems
SI	Spark ignition (gasoline) vehicle
SOX	Sulfur oxides
SUV	Sport utility vehicle
TDM	Transportation demand management
TTW	Tank-to-wheel
USD	United States dollars
VOC	Volatile organic compounds
VLT	Variable valve lift and timing
WTT	Well-to-tank
WTW	Well-to-wheel

Acronyms

AIST	National Institute of Advanced Industrial Science and Technology
AMVER	Automated Mutual-Assistance Vessel Rescue System
CCFA	Comité des Constructeurs Français d'Automobiles
CICERO	Centre for International Climate and Environmental Research-Oslo
ETP	<i>Energy Technology Perspectives</i>
FSU	Former Soviet Union
GE	General Electric
GFEI	Global Fuel Economy Initiative
GPOA	G8 Gleneagles Plan of Action
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IEA	International Energy Agency
IMO	UN International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change

ITF	International Transport Forum
ISO	International Standards Organisation
MARPOL	International Convention for the Prevention of Pollution From Ships
MDG	Millennium Development Goals
MIT	Massachusetts Institute of Technology
MoMo	Mobility Model (IEA)
NHTSA	US National Highway Transportation Safety Administration
NREL	US National Renewable Energy Laboratory
OPRF	Japanese Ocean Policy Research Foundation
RMI	Rocky Mountain Institute
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
US DOT	United States Department of Transportation
US EPA	United States Environmental Protection Administration
USGS	United States Geological Survey
WBCSD	World Business Council for Sustainable Development
WHO	World Health Organisation

Units

°C	degrees Celsius
atm	atmosphere (unit of pressure)
bar	a unit of pressure nearly identical to an atmosphere unit. 1 bar = 0.9869 atm (normal atmospheric pressure is defined as atmosphere)
bbl	barrel
bcm	billion cubic metres
boe	barrels of oil equivalent. 1 boe = 159 litres
EJ	exajoule = 10^{18} joules

g	gram
g CO ₂ /km	grams CO ₂ per kilometre
g CO ₂ eq/km	grams CO ₂ equivalent per kilometre
g CO ₂ /kWh	grams CO ₂ per kilowatt hour
g CO ₂ eq/kWh	grams CO ₂ equivalent per kilowatt hour
g/km	grams per kilometre
GJ	gigajoule = 10 ⁹ joules
Gt	gigatonne = 10 ⁹ tonnes (1 tonne x 10 ⁹)
GW	gigawatt = 10 ⁹ watts
GWh	Gigawatt hour
ha	hectare
h	hour
kg	kilogram
km	kilometre
kt	kilotonnes
ktoe	kilotonnes of oil equivalent
kW	kilowatt = 10 ³ watts
kWh	kilowatt hour
L	litre
Lge	litre gasoline equivalent
m ²	square metre
m ³	cubic metre
Mbd	million barrels per day
Mbtu	million British thermal units
Mha	million hectares
MJ	megajoule = 10 ⁶ joules
mm	millimetre
MPa	Megapascal
mpg	miles per gallon
Mt	megatonne = 10 ⁶ tonnes

Mtoe	million tonnes of oil equivalent
MW	megawatt = 10^6 watts
mW/m ²	milliwatt per square metre
MWh	megawatt-hour
Pa	Pascal
PJ	petajoule = 10^{15} joules
pkm	Passenger kilometre
pWh	petaWatt-hours
t	tonne = metric ton = 1 000 kilogrammes
t/h	tonnes per hour
TEU	Twenty-foot equivalent units
tkm	tonne kilometre
toe	tonne of oil equivalent
TW	terawatt = 10^{12} watts
TWh	terawatt-hour
W	watt
A	ampere
MWe	megawatt electrical
Nm ³	normal cubic metre (at 0 degrees Celsius and at a pressure of 1.013 bar)
ppbv	parts per billion by volume
ppm	parts per million
V	Volt
vkm	Vehicle kilometre
μm	micrometer

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