Technology Roadmap

Fuel Economy of Road Vehicles

International Energy Agency

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
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International Energy Agency

International Energy Agency
9 rue de la Fédération
75739 Paris Cedex 15, France

www.iea.org

Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of carbon dioxide (CO_2) will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse-gas (GHG) emission goals. Every major country and sector of the economy must be involved. The task is also urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is leading the development of a series of roadmaps for some of the most important technologies. By identifying the steps needed to accelerate the implementation of radical technology changes, these roadmaps will enable governments, industry and financial partners to make the right choices. This will in turn help societies make the right decisions.

Over 50% of oil use around the world is for transport and three-quarters of the energy used in the transport sector is consumed on the roads. The IEA *Energy Technology Perspectives 2012* (*ETP 2012*; IEA, 2012b) projects that without strong new policies, road transport sector fuel use will double between 2010 and 2050. Yet one of the most cost-effective ways to moderate growth in oil demand across all sectors is to improve the efficiency of transport vehicles. This roadmap focuses on existing low-cost fuel efficiency technologies, how much they could improve efficiency, and how this potential can be realised, especially via government policies. It covers a range of road vehicle types, including cars, trucks and motorised two-wheelers, and provides milestones on the road to a much more efficient fleet of vehicles by 2030, based largely on actions that should be taken in the next five to ten years.

Unlike many IEA technology roadmaps, this roadmap does not need to provide a detailed strategy on technology research and development, or on deploying expensive new technologies. Most of the technologies covered in this roadmap are already available, commercially viable and cost-effective. This message is much more about overcoming market failures – especially a lack of interest or awareness that holds consumers back from buying vehicles with the latest technology to improve fuel economy. There are many reasons for this. Consumers lack good information on fuel economy and often doubt that vehicles can really save them significant money on fuel costs. But consumers do greatly benefit from the policies that overcome these market failures, typically with fuel savings over a few years that pay for the cost of the improvements. Society as a whole benefits greatly from low-cost fuel savings – economically and in terms of improved energy security and lower GHG emissions.

It is crucial that governments around the world tackle the problem of poor vehicle fuel economy, and this document provides important guidance. Countries should explore how much fuel economy improvement is possible by different dates and design policies to push for maximum improvements over the coming 10 to 15 years. This roadmap and the companion IEA document *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a) provide policy makers with the guidance they need to develop their own plans and policies to make progress toward an efficient vehicle future.

Maria van der Hoeven
Executive Director

This roadmap was prepared in 2012. It was drafted by the IEA Energy Technology Policy Division. This paper reflects the views of the International Energy Agency (IEA) Secretariat, but does not necessarily reflect those of IEA member countries. For further information, please contact the author at: transportinfo@iea.org.

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The resulting document is the IEA interpretation of these workshops, with additional information incorporated to provide a more complete picture, and does not necessarily represent the views of all the workshop participants and reviewers.

Speakers at ITF/OECD round table on "Stimulating low-carbon vehicle technologies" (Paris, 18-19 February 2010)

Luc Bastard, Renault and CCFA, France
Jo Van Biesebroeck, K.U. Leuven, Belgium
Nils Axel Braathen, OECD, Environment Directorate
Don Fullerton, University of Illinois, Champaign, United States
David Greene, Oak Ridge National Laboratory, Transportation Research Center, United States

Speakers at IEA freight truck fuel economy workshop, challenge Bibendum, 20-21 May 2011

Peter Brunner, EU Commission
Cheryl Bynum, EPA, United States
Duleep Gopalakrishnan, ICFI, United States
Nikolas Hill, AEAT, United Kingdom
Hiroshi Hirai, JARI, Japan
Julia King, Aston University, United Kingdom
Drew Kodjak, ICCT, United States
Stefan Larsson, ACEA, Europe
Anders Lundström, Scania, Sweden
Takashi Naono, MLIT, Japan

For more information on this document, contact:

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

Key findings

- **Most technologies for improving the fuel economy of two-wheelers, light-duty vehicles (LDV) and heavy-duty vehicles (HDV) are already commercially available and cost-effective.** Compared with 2005 levels, the potential for improving the fuel economy of all vehicle types within the 2030 time frame ranges from 30% to 50%. This represents a very important opportunity for saving oil and cutting carbon dioxide (CO_2) over the coming two decades and beyond. Fuel efficiency accounts for 4.5 gigatonnes of CO_2 ($GtCO_2$) reduction in the 2DS compared to 6DS in 2050, representing 50% of total emissions reductions in the transport sector.

- **Although many fuel-saving technologies are already commercially available and cost-effective, particularly when considered over the lifetime of vehicles, their market penetration is often low because of a range of barriers explained in this roadmap.** Strong policies are needed to ensure that the full potential of these technologies is achieved over the next 10 to 20 years.

- **Some technologies need additional research to become commercially viable**, including waste heat recovery devices, electromechanical valve actuation, low-friction lubricants and some lightweight materials. New propulsion systems requiring new fuels, such as plug-in electric vehicle systems and fuel cell systems, are beyond the scope of this roadmap and are treated in separate roadmaps.

- **There is often a gap between the fuel economy measured in vehicle tests and in-use vehicle performance.** This gap can be up to 20% and must be reduced to minimise actual fuel use. Strategies to close this gap include better design of fuel economy test cycles, improved traffic flow and better road surface conditions. "Eco-driving", which includes a suite of technologies and actions to improve driving styles and vehicle operating characteristics, also has significant potential to improve fuel economy.

- **Policies that promote fuel economy technologies and improve tested and in-use fuel economy, including fuel economy standards, fiscal measures and information/education programmes, will play a critical role in maximising fuel economy improvements in all countries over the coming decades.** These are introduced in this roadmap and investigated in greater depth in *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a) (Box 1).

- **Fuel economy standards are in place in most OECD member countries and China, and are helping to make important progress** in these countries. These can be used as guides for other countries seeking to improve fuel economy. Most major economies should aim to implement fuel economy standards, as part of a comprehensive fuel economy policy package, by 2015, with strong fuel economy improvement targets for 2020 and even out to 2030. Important complementary policies include fuel economy labelling, fuel economy or CO_2-adjusted vehicle tax systems (such as "feebates"), and fuel taxes.

- **In countries that already have strong policies, these policies and their targets should be tightened to maintain progress, and by 2015, extended to 2030** and expanded to cover all road vehicle types, particularly heavy duty vehicles.

- **This roadmap includes a new fuel economy readiness index, which measures the extent to which countries have implemented steps** that will fully exploit the potential of existing fuel economy technologies and maximise their use in vehicles. The index is built from the four key policies needed to improve fuel economy: fuel tax, CO_2-based vehicle tax, fuel economy standards and labelling.

This roadmap provides additional recommendations that should be considered in order to successfully set and meet fuel economy technology milestones and strategic goals. These include:

- **Establish fuel economy and/or CO_2 emission targets for light-duty vehicles and trucks, and use a mix of policies that provide a clear framework and balance stakeholder interests.** To give automakers and other interested parties a clear view, governments should establish policy frameworks for the period at least to 2025. As far as possible, policies should not favour particular technologies but rather promote improved fuel economy in general, encouraging good practice and performance. Policy goals should be grounded in societal goals such as energy security and low CO_2 emissions.

- **Address policy and industry needs at a national level.** Governments should work diligently to enact policies that support the necessary technology development and dissemination. The policy recommendations in this document are a good place to start. National roadmaps can be developed that set national targets and help interested parties to set their own appropriate targets, guide market introduction, understand consumer behaviour, craft supportive policy and collaborate. By formulating common goals, targets and plans, countries and the global community can help accelerate progress toward an efficient vehicle future.

- **Research, development, demonstration and deployment (RDD&D) of advanced fuel economy technologies is still needed.** Even though most of the key fuel economy technologies are available today, additional breakthroughs and cost reductions would help, including lighter materials, advanced combustion systems and better lubricants. Internationally co-ordinated programmes involving governments and automobile manufacturers will help trigger a faster development and uptake of new technologies in the 2020 time frame and beyond.

- **Increase international collaboration on fuel economy.** Countries should increase collaboration, for example by aligning targets and policy designs, wherever possible – particularly countries in the same region with interconnected markets (*e.g.* Europe, South Asia, South America, etc.). By providing broadly consistent signals to consumers and automakers, countries can increase the strength of their combined efforts, while helping manufacturers to sell more of their fuel-efficient models, potentially lowering the cost of compliance. Lower costs are ultimately passed on to consumers and reduce the overall cost of achieving energy security and climate change goals.

The IEA will continue to work with governments and stakeholder organisations to co-ordinate activities identified in this roadmap and monitor and report on progress toward identified goals and milestones.

Box 1. *Policy Pathway: Improving the Fuel Economy of Road Vehicles*

The IEA publication *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a) offers detailed guidance for governments on how to put in place policy measures to increase the fuel efficiency of road vehicles. It presents the key steps in the planning, implementation, monitoring and evaluation of policy instruments related to vehicle fuel economy, including standards, fiscal measures and labelling. Case studies are provided of the European CO_2 emissions regulation for light-duty passenger cars and the Japanese heavy-duty vehicle fuel economy standards. The Policy Pathways series is designed for policy makers at all levels of government and other relevant stakeholders who seek practical ways to develop, support, monitor or modify energy efficiency policies in their home country and abroad.

Roadmap purpose and scope

The primary purpose of this roadmap is to help establish a vision for vehicle fuel economy, promote specific targets, and outline key steps to achieve them. This roadmap also outlines roles for different stakeholders and describes how they can work together to reach common objectives. Finally, it introduces key elements of policy, which are further explored in *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a).

The *Technology Roadmap: Fuel Economy of Road Vehicles* has been developed in collaboration with governments, industry and non-government organisations (NGOs). A key partner has been the Global Fuel Economy Initiative (GFEI) and its members: the International Transport Forum (ITF), the FIA-Foundation, the International Council on Clean Transportation (ICCT) and the United Nations Environment Programme (UNEP). This roadmap builds on recent analysis, conferences and reports from this initiative. It is also based on the results of two specific workshops, one for light-duty vehicles (February 2010) and one on trucks (May 2011).

This roadmap covers technologies associated with fuel economy improvement in conventional internal combustion engine (ICE) vehicles, including two-wheelers, cars and trucks. Hybrid-electric engine systems are included among these technologies to improve ICE efficiency, but other advanced propulsion systems, such as pure battery-electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCEVs), are covered under separate roadmaps. An updated EV/PHEV technology roadmap and a biofuels for transport technology roadmap were published in 2011. A roadmap for FCEVs is planned for 2013. The technology and related projections in this roadmap were developed using the IEA Mobility Model (Box 2).

While this roadmap covers vehicles and fuel economy potential globally, it acknowledges that vehicle markets and economics can differ markedly from country to country. Most technologies are widely available and are already in use in vehicles all over the world, but cost-effectiveness can vary depending on each country's situation, as can the sales of different types of vehicles and thus the applicability of different technologies.

Box 2. IEA Mobility Model (MoMo)

Over the past ten years, the IEA has developed the Mobility Model, a global transport spreadsheet model that allows projections and policy analysis to 2050, with considerable regional and technological detail. It includes all transport modes and most vehicle and technology types, including two- and three-wheelers, passenger cars, light trucks, medium and heavy freight trucks, buses and non-road modes (rail, air and shipping). MoMo is linked to the ETP optimisation model and was used to produce the underlying analysis of the Energy Technology Perspectives publication series.

MoMo covers 29 countries and regions. It contains assumptions on technology availability and cost at different points in the future, how costs could drop if technologies are deployed at a commercial scale, and other features. It, therefore, allows detailed bottom-up "what-if" modelling, especially for passenger LDVs and trucks. Energy use is estimated using an adapted version of the ASIF (activity-structure-intensity-fuel) methodology known as PUCE, which works to ensure consistency between the vehicle Parc (stocks), Utilisation (travel per vehicle), Consumption (energy use per vehicle, *i.e.* fuel economy) and Emissions (fuel CO_2 emission factors).

MoMo is used to produce projections of vehicle sales, stocks, travel, energy use, GHG emissions (on a vehicle and well-to-wheel basis) and pollutant emissions for all modes. It allows a comparison of marginal costs of technologies and total cost across all modes and regions for a given scenario. For example, a recent MoMo-based analysis estimates that the baseline cost for all vehicles and fuel to 2050 will be on the order of USD 400 trillion worldwide; a low-carbon scenario does not change this number appreciably, and could be lower.

More information on MoMo is provided in *Transport, Energy and CO_2: Moving Toward Sustainability* (IEA, 2009).

New vehicle fuel economy status today

Most passenger light-duty vehicles are bought and driven by private consumers, though a significant proportion are in business fleets. Most consumers choose LDVs not on a cost-minimising basis, but with many attributes in mind, including size, comfort, style, engine power, safety and reliability. Consumers may care little about fuel economy, particularly when fuel prices are low, so manufacturers have not in general fully exploited available technologies to optimise fuel economy.

The fuel economy of automobiles was not a concern until the first oil crisis of 1973, when vehicle buyers started to pay more attention to running costs.

Many terms are used to define the quantity of energy needed to cover a certain driving distance, and governments have put in place a wide variety of methodologies to measure fuel economy under comparable and repeatable circumstances, using a variety of units (Box 3).

The tested fuel economy of new light-duty vehicles has tended to be flat in most OECD countries over the past two decades (Figure 1). Though there have been net improvements in some countries, other countries have performed worse over time, mainly because of a shift towards bigger, more powerful vehicles. Since 2003, however, nearly all OECD countries have started to improve. In non-OECD countries, historical data has been scarce until recently.

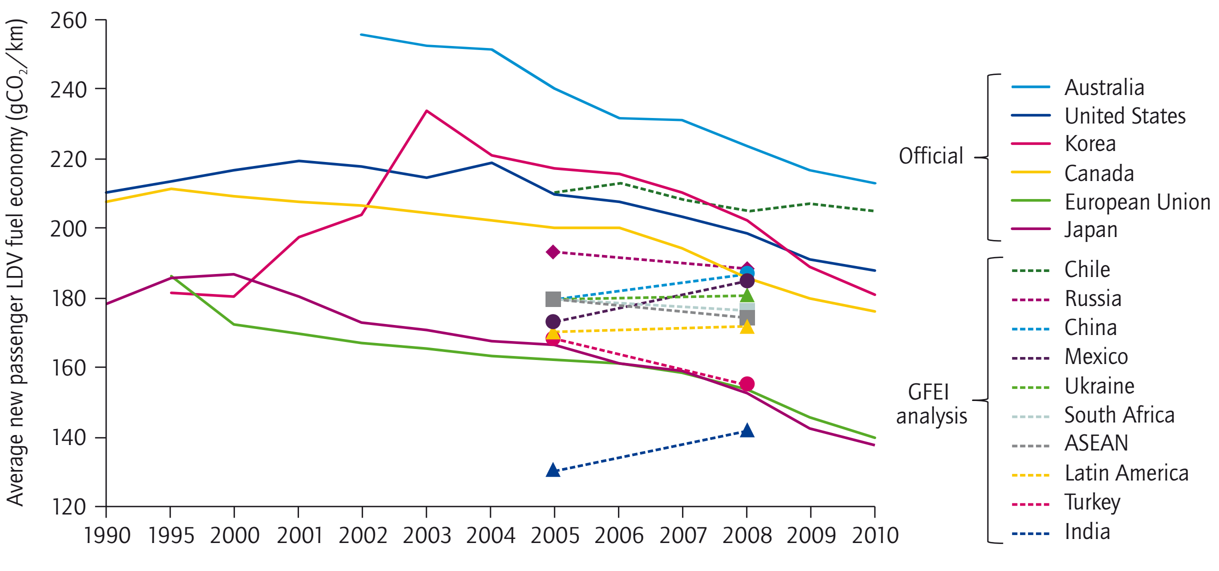
In conjunction with the GFEI, the IEA recently published *International Comparison of Light Duty Vehicle Fuel Economy and Related Characteristics* (GFEI, 2011). This report aims at determining the global average fuel economy of cars in 2005 and 2008, establishing a base year number and estimating a three-year trend as an initial indicator of whether the global fuel economy is headed in the right direction. The GFEI target is to halve new car fuel consumption between 2005 and 2030.

The study, which covered more than 80% of the new vehicles sold in 2005 and 2008, analysed the evolution and effects of key power train characteristics, such as engine size and power. Global average new vehicle fuel economy in 2005 was found to be about 8 litres of gasoline equivalent per 100 kilometres (Lge/100 km). There were wide differences from country to country, and progress over the three-year period ranged from a 3.7% yearly improvement to a 3% annual worsening of average new vehicle fuel economy (Figure 3).

The large differences between countries' "starting points" in 2005 are mainly due to variations in the average size, weight and power of cars, and in technology on cars of a similar size and weight. Those differences can be explained in turn by differences in policies, incomes, geography and culture; in Europe, for example, many people buy small cars to improve their chances of parking on urban streets, which is less of a concern in North America.

Average fuel price is also an important factor, but since there is a world oil price, most national differences in fuel prices are related to fuel taxation policy. Existing fuel economy regulations can also have a major impact on average fuel economy, especially where

Figure 1. Average new passenger LDV tested fuel economy by country/region, 1990-2011



Box 3. Fuel economy: some relevant definitions

Whether expressed as the ratio of the quantity of energy needed to drive a certain distance, or as the distance covered with a given quantity of energy, fuel economy of motorised vehicles represents the efficiency of the conversion of energy contained in the fuel to mechanical energy at the wheels that drive the vehicle (measured as distance travelled). Typically the term "fuel economy" is used to relate vehicle driving distance to unit energy, often as a volume, to give units such as miles per gallon (mpg) or litres per 100 kilometres (L/100 km). It can also be expressed in grams of CO_2 per kilometre, since tailpipe CO_2 is almost perfectly correlated with fuel use for any specific type of fuel. The European Union now typically measures fuel economy in grams of tailpipe CO_2 emissions per kilometre.

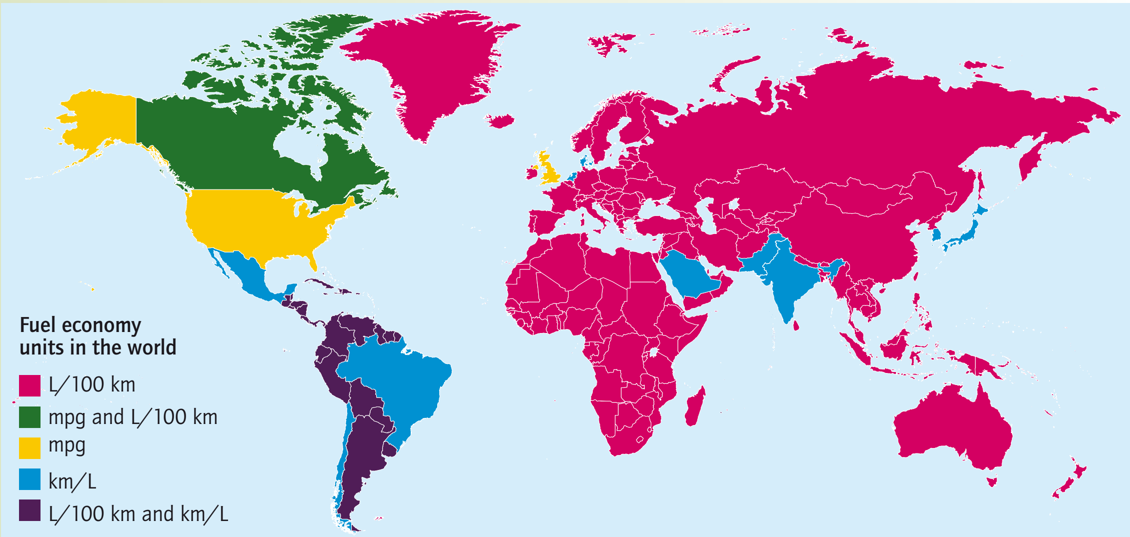
The terms "fuel efficiency" and "fuel intensity" are used interchangeably with fuel economy in this report. For vehicles, the term "efficiency" itself can have a range of meanings, such as the efficiency of an engine in converting energy into power, or the energy efficiency of moving a vehicle taking into account its weight (*e.g.* litres per tonne-km). This report focuses on vehicle fuel economy, *i.e.* energy per distance moved, regardless of vehicle weight, engine power or any other factor, except where otherwise indicated.

Different units are typically used to express fuel economy in countries across the world (Figure 2).

Vehicle fuel economy only represents one part of the overall transport energy chain; before energy can be used in a vehicle, it must be produced, transported and loaded onto the vehicle. The "full fuel life-cycle" approach takes this complete picture into account, with "well-to-tank" as well as "tank-to-wheel" efficiencies considered. The conversion energy needed to transform the primary source of energy into the final form of energy (*e.g.* crude oil into gasoline or diesel, bio-feedstocks into alcohol or biodiesel, etc.) can play an important role in determining the overall efficiency (and net CO_2 emissions) of various vehicle/fuel combinations. Since this report focuses on vehicles, it covers the "tank-to-wheel" part of the fuel cycle, where technical improvements to ICE vehicles have an effect. The effects of substituting different fuels, and the "well-to-tank" emissions of producing fuels, are not considered in detail. Other IEA roadmaps, such as those covering biofuels and EVs, address these "well-to-tank" issues (IEA, 2011a and 2011b).

Other relevant definitions can be found in the glossary.

Figure 2. Fuel economy units used by country



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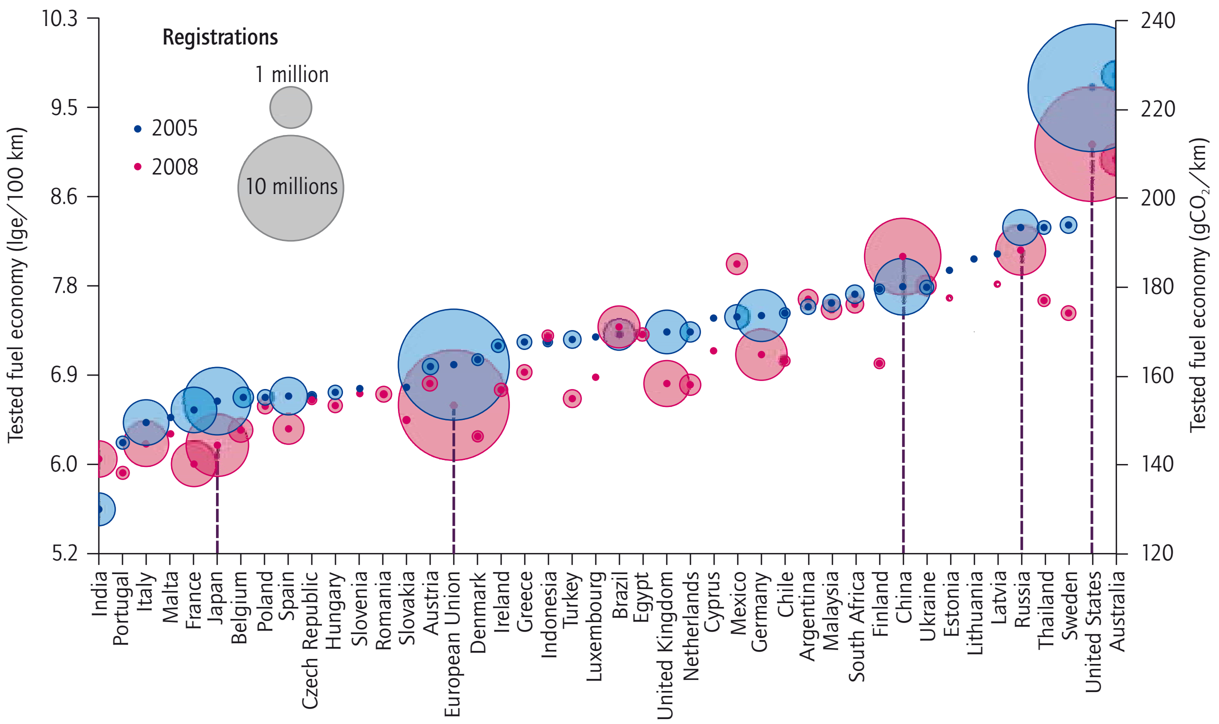
Source: unless otherwise indicated, material in figures and tables derives from IEA data and analysis.

Note: the US and UK (imperial) gallons are different volumes.

Figure 3. Average fuel economy and new vehicles registrations, 2005 and 2008



vehicle ownership taxes have been linked to vehicles' fuel economy or CO_2 emissions ratings.[1]

The large global dataset for 2005 and 2008 gives a first glimpse of global fuel economy trends. Although the GFEI target of reducing new vehicle fuel consumption by 50% by 2030 is ambitious, it is achievable, as it assumes rates of change that have been reached by several countries or regions recently. The fuel economy of new vehicles in OECD and non-OECD countries did not improve quickly enough from 2005 to 2008 to reach the 2030 target, however, so more effort is needed to shift these trends (Table 1). About a 2.7% annual rate of improvement globally is needed from 2005 to 2030; but given the slower rate achieved through 2008, the required rate is actually about 3% starting from 2008. Some countries will probably need to move even faster for the global average to achieve this pace and reach the 2030 target.

The study showed that average fuel economy in OECD countries was worse than in non-OECD countries in 2005, but improved between 2005 and 2008 to reach parity with non-OECD countries, whose average fuel economy actually become slightly worse in this period. This reflects several trends in market development and policy application.

OECD vehicles were larger in 2005 than in 2008, but non-OECD country vehicles are increasing

1 The *Policy Pathway: Improving the Fuel Economy of Road Vehicles* investigates these policy options in more detail.

Table 1. Fuel economy status worldwide and long-term GFEI objective (Lge/100 km)

	2005	2008	2030	Annual change 2005-08	Required annual change 2005-30
OECD average	8.21	7.66		-2.1%	
Non-OECD average	7.49	7.68		0.3%	
Global average	8.07	7.67		-1.7%	
GFEI objective	8.07		4.03		-2.7%

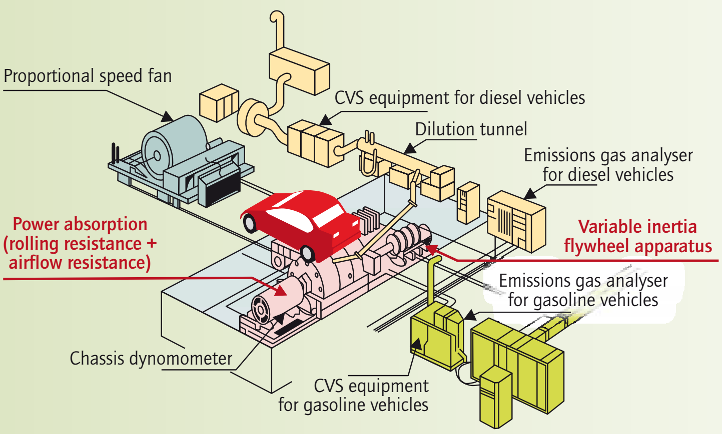
in size. OECD countries also have both the most fuel-efficient small vehicles, and the most CO_2-intensive big vehicles (with many more big vehicles than non-OECD countries). The ranges of vehicles and technologies are more developed in OECD countries, offering high-tech small and medium-size vehicles (and even small, efficient sport-utility vehicles, or SUVs) to the car buyer. The vehicle models portfolio in non-OECD markets appears to be less technically advanced but is changing quickly as more vehicles become available internationally.

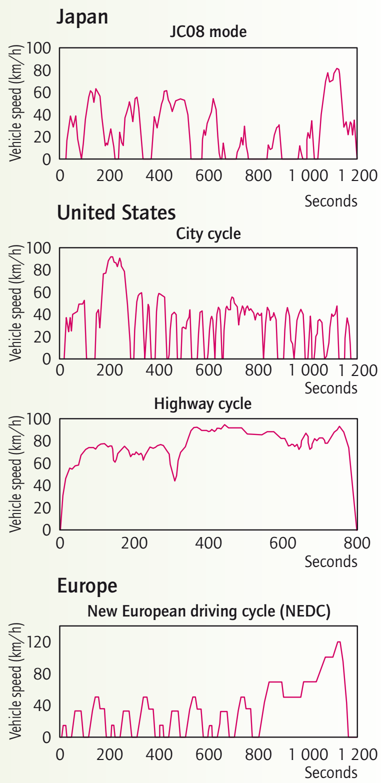
Little information is available for most countries regarding the average fuel economy of other motorised road vehicles, such as two-wheelers and trucks, but there are some data that show a significant difference in the average fuel economy of long-haul tractor-trailers ("semis") between the United States and Europe (Cooper *et al.*, 2009). In the United States, the representative truck averages about 40 L/100 km, with around 75% average load capacity. In the United Kingdom, similar trucks average 35 L/100 km to 36 L/100 km, but with a lower average load factor of around 50% (McKinnon, 2009). This difference is partly explained by the higher average power of US trucks and may also be related to the fact that most European trucks are equipped with an automated manual transmission compared with manual transmission in the United States.

Box 4. Fuel economy testing

To compare the fuel economy of different vehicles in a consistent and unbiased manner, a systematic approach must be used. Official fuel economy estimates are usually measured in a "homologation" laboratory under careful test conditions. A range of standardised driving cycles has been developed to simulate typical driving conditions, and is used to measure both fuel economy and pollutant emissions, such as carbon monoxide (CO), hydrocarbons (HC), particulate matters (PM) and nitrogen oxides (NO_x). The layout of a passenger car in the testing laboratory is such an expensive piece of equipment that not all countries can afford to perform independent tests (Figure 4).

Figure 4. Vehicle testing layout, with typical test cycles for three regions





Source: JAMA, 2008.

Box 4. Fuel economy testing (continued)

Testing for trucks has some additional considerations. Given the size and weight of trucks, often only the engine is tested on a bench dynamometer to obtain pollutant and fuel economy measurements. Test cycles have tended to be relatively simple, but as fuel economy regulations for trucks are introduced, new test cycles for trucks are being considered and some truck manufacturers have called for a standardised international approach to truck fuel economy testing (ACEA, 2009).

Four approaches to measuring fuel economy can be distinguished (Table 2). There are numerous possible configurations of trucks, so homologating each is not realistic. Computer simulation of the whole truck (typically in combination with engine testing on a bench dynamometer) seems to be the option favoured by industry and increasingly by governments. The Greenhouse Gas Emissions Model (GEM) simulation tool developed in the United States adopts this strategy, complementing the vehicle modelling tool with engine dyno tests. China is planning to use chassis dyno tests for main truck families and computer simulation for variants. More detail on testing methods and driving cycles is available in the IEA *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a).

Table 2. Tests and simulation options for measurement of vehicle fuel economy

Type of test	*Part simulated*	*Test cost*	*Countries considering fuel economy type approval of trucks*
On-road	None	Low	
Chassis dyno	Road	Very high	China
Engino dyno	Road and non-engine components	High	Japan, United States, European Union
Computer simulation	All	Low	United States, European Union, Japan, China

Roadmap vision: fuel economy improvement and impacts on energy use and CO_2

The vision of this roadmap is to improve road vehicle fuel economy according to the 2°C Scenario (2DS) described in *ETP 2012* (IEA, 2012b), whereby energy-related CO_2 emissions are halved by 2050, helping to limit the global average temperature rise to 2°C (see Box 5). This involves new road vehicles achieving substantial fuel economy improvements by 2030, leading to substantial reductions in fuel consumption by that year and well beyond, as the entire stock of vehicles is eventually replaced. For new light-duty vehicles, the 2DS targets are consistent with the GFEI targets – 50% reduction in litres per 100 km between 2005 and 2030, from about 8 L/100 km to 4 L/100 km worldwide, with a resulting 50% reduction in the fuel use of all cars on the road by 2050. For two-wheelers and trucks, different targets are set as described below.

Fuel economy improvements in conventional vehicles will be critical to achieving a maximum temperature rise of 2°C; even with a rapid increase in sales of electric and hybrid vehicles, conventional ICE vehicles will continue to dominate the market until 2030 (Figure 5). By making these vehicles much more efficient, considerable fuel savings and CO_2 reductions can be obtained.

As outlined in IEA (2009), a range of well-known technologies exist – most of them already commercial – that if fully adopted and exploited for fuel economy improvement could help reach this roadmap's vision but the context for this projection deserves further consideration.

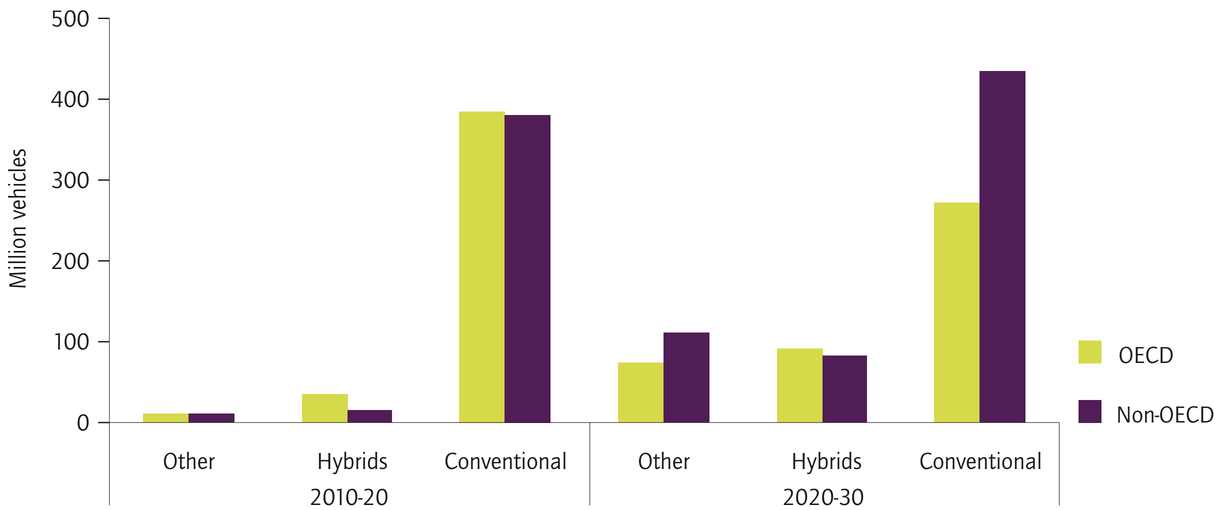
The *Fuel Economy Roadmap* vision

To reduce fuel use per kilometre by 30% to 50% in new road vehicles worldwide in 2030, and from all vehicles by 2050, in order to significantly reduce GHG emissions and oil use, compared with a baseline projection.

First, considerable improvements and fuel savings are expected to occur given current policies – *i.e.* in the 6°C Scenario (6DS) described in *ETP 2012* (IEA, 2012b) – such as existing fuel economy standards for LDVs in most OECD countries and China through at least 2015. Some autonomous improvements in fuel economy for cars and (especially) trucks can also be assumed to occur in countries with no standards, and everywhere after 2020 (since in the 6DS, standards are not assumed to be extended). Out to 2050, these baseline savings are substantial; compared with a scenario in which vehicle efficiency is frozen at 2010 levels, the baseline fuel economy improvements yield in excess of 50 exajoules (EJ) or 4 $GtCO_2$. These savings could be lower or higher depending on variables including fuel prices, incomes and technology costs. In particular, fuel economy improvement for trucks has not reached the rates that many thought the market would routinely deliver.

As part of the cost minimising strategy used in the *ETP 2012* (IEA, 2012b) modelling framework, fuel economy improvement is generally the least expensive strategy available to the transport sector in

Figure 5. Light-duty vehicle sales in 2DS, worldwide, by technology type and time period (total sales over indicated time frame, in millions)



Box 5. *ETP 2012* 2°C Scenario (2DS)

The basis for this roadmap is the IEA *ETP 2012* (IEA, 2012b) 2°C Scenario (2DS), which describes how energy technologies across all energy sectors could be transformed by 2050 to achieve the global goal of reducing annual CO_2 emission levels to half those of 2005 (IEA, 2012b). The model used for this analysis is a bottom-up TIMES model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The *ETP* model is a global 29-region model that permits the analysis of fuel and technology choices throughout the energy system. The model's detailed representation of technology options includes about 100 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. In addition, the *ETP* model is supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors (see Box 2 on IEA Mobility Model).

ETP 2012 considers other scenarios. The *ETP 2012* 6°C Scenario (6DS) assumes that no major new policies to reduce GHG emissions will be introduced in the coming decades. The 6DS is considered to be the baseline scenario in the Technology Roadmap series. Achieving the 2DS will be difficult; some of its assumed rates of change (*e.g.* annual change in sales of new technologies) are unprecedented. To achieve such a scenario, strong policies will be needed from governments around the world.

the near term, so plays a prominent role. Thus in 2DS, significant additional fuel economy improvement occurs, thanks to strong uptake of new technologies, triggered by strong efficiency policies for all transport modes in all countries. LDVs halve their average fuel consumption; medium and heavy trucks by about 30%; two-wheelers by 20% (Table 3). These should be considered targets based on estimates of best achievable levels, given what is known about technology potential. These also take into account expected changes in sales across different parts of the world, so are not purely technical estimates. Finally, they reflect some increases in vehicle size, weight and power – though in fact they assume that these attributes are held near current levels rather than allowed to increase with no checks; exceptions are made for trucks, which are assumed to get larger as appropriate given the potential for more efficient delivery of goods with larger trucks, and for two-wheelers, which are assumed to increase in size in non-OECD countries (especially in Asia), where they are currently very small on average.

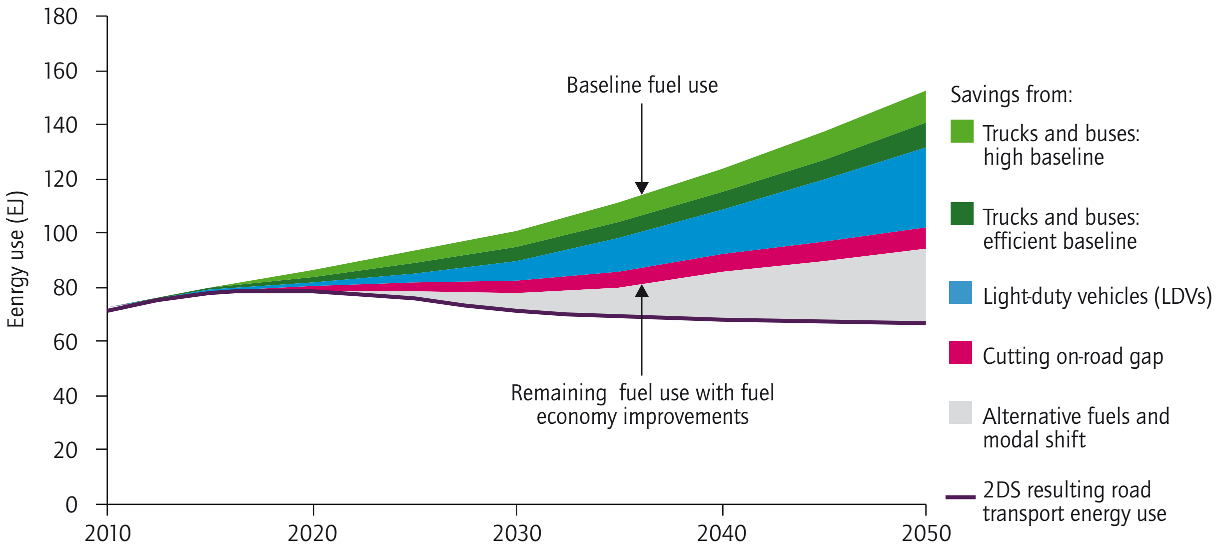
The fuel savings from new LDVs, trucks and two-wheelers that result from these fuel economy improvements in the 2DS scenario compared with the 6DS scenario increase over time and reach 50 EJ across all modes by 2050 (Figure 6). Most savings occur in passenger LDVs, mainly because they represent the majority of fuel use, and are likely to continue to do so in the coming decades.

There is less improvement in the baseline for LDVs than there is for trucks. However, the improvement

Table 3. Average new vehicle fuel economy (Lge/100 km) by mode and year, 2DS

	2005	2010	2020	2030	Average annual % improvement, 2005-30
Passenger LDVs	8.1	7.6	5.4	4.1	-2.7%
Light/medium trucks	13.7	13.4	10.7	9.5	-1.5%
Heavy trucks and buses	39.1	35.9	31.8	27.1	-1.5%
Two-wheelers	2.8	2.9	2.6	2.3	-0.8%

Figure 6. Energy savings from fuel economy improvements



Note: two-wheelers' energy savings do not show up, as the savings are too small to be visible.

in the baseline for trucks is uncertain; the assumption that as commercial ventures, truck operators will seek out the most efficient vehicles depends on many factors. There is increasing evidence that truckers use a fairly short payback period for fuel efficiency decisions (approximately three years according to Duleep, 2011), which is inconsistent with an approach that is optimal for society. For these reasons we consider two possibilities, a less efficient and a more efficient baseline for trucking (Figure 6).

The energy savings from in-use fuel economy improvements are also considered.[2] If the gap in fuel efficiency between tested and in-use conditions can be cut in half, to a 10% difference instead of a current estimated world average gap of 20% (ICCT, 2012), this would save an additional 15 EJ in 2050 and result in an almost flat trend in remaining road transport fuel consumption worldwide. Thus the combination of the new vehicle fuel economy improvements and in-use improvements outlined here would be sufficient to prevent significant increases in road fuel use after 2020 worldwide.

Vehicles, fuel use and CO_2

In 2009, road vehicles (cars, trucks, buses, two-wheelers) accounted for almost three-quarters of transportation fuel use around the world, with most of the rest used by ships and aircraft (Figure 7). Light-duty vehicles (cars and "passenger light trucks", including SUVs, minivans and personal pick-up trucks) account for well over half of road usage.

The *ETP 2012* (IEA, 2012b) 6DS scenario shows strong increases in fuel use in all road modes, with total fuel use doubling between 2010 and 2050. Since nearly all vehicles use predominantly petroleum fuels, CO_2 emissions rise at a similar rate. In 2010, cars emitted just over 2 $GtCO_2$ worldwide on a well-to-wheel (WTW) basis (about 85% from the fuel combustion in the vehicle and 15% from fuel production and distribution), passenger light trucks just over 1 $GtCO_2$, and freight trucks about 1.8 $GtCO_2$ (Figure 8). Emissions were much smaller for buses (about 0.5 $GtCO_2$) and two-wheelers (about 0.2 $GtCO_2$). In the *ETP 2012* 4DS scenario, road vehicles reach a combined 8 $GtCO_2$ by 2030 and 12 $GtCO_2$ by 2050, with the fastest growth and largest overall increases coming from passenger cars and light trucks.

In the *ETP 2012* 2DS (here including all technologies such as EVs, FCEVs and PHEVs), energy use and CO_2 emissions are cut dramatically by 2050, with more than half of these reductions coming from fuel economy improvements to conventional ICE vehicles (covered in this roadmap) and the rest from adoption of new vehicle propulsion technologies and fuels (IEA 2011a and 2011b).

2 In-use fuel economy refers to real life fuel economy, taking into account not only vehicle performance (as for the tested fuel economy), but also driver behaviour and road conditions. In-use fuel economy improvement potential is addressed later in the report.

Figure 7. World transport energy use by mode, 1971-2009

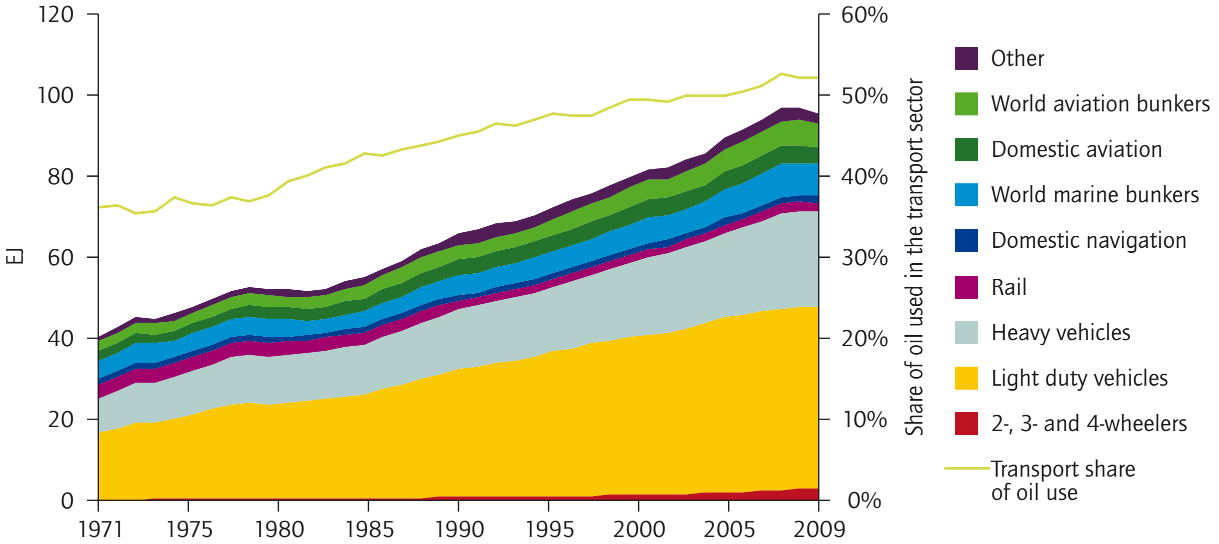
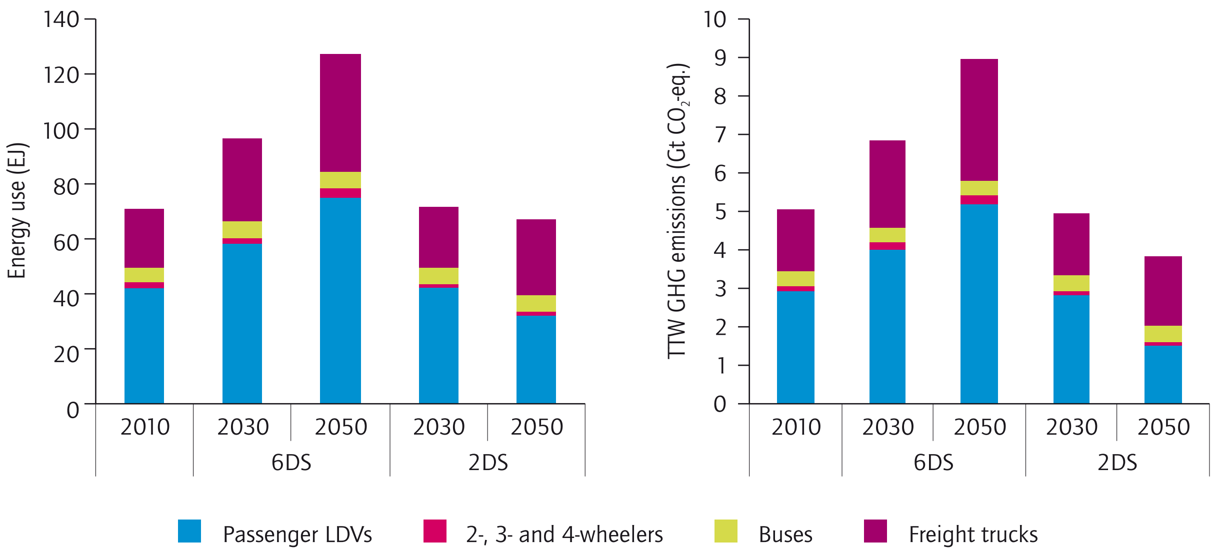


Figure 8. Road fuel use and CO_2 by vehicle type in *ETP 2012* scenarios



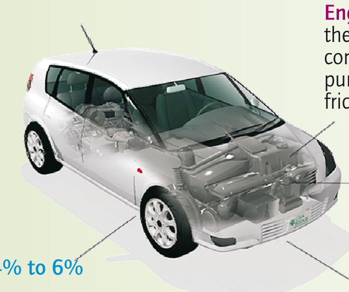
Improving vehicle fuel economy: technologies and measures

An extensive range of technologies is available for improving vehicle fuel economy. Most are commercially available and have some market penetration but could be used more extensively; others are new or too expensive to be widely used yet. The overall potential for applying these technologies to cars, trucks and two-wheelers, however, has been demonstrated to be large (Box 6). Alternative fuels are also available (including biofuels, natural gas and electricity) that generate less CO_2. In this report the focus remains on the technical efficiency of ICE vehicles, without particular consideration for fuel type (most technologies can be used on a full range of liquid and gaseous fuel vehicles).

Box 6. Where the energy goes

Only about one-fifth of the energy contained in a litre of fuel is used to propel a vehicle, so there is huge potential for improvement. Most losses are from the power train (Figure 9) especially from waste heat from the engine exhaust, coolant and brake pads. Turbo chargers can recover some of the waste heat, leading to a more efficient combustion cycle. Although widely used in the power generation industry, the Rankine cycle, which converts heat to power, is still at prototype stage in the automotive industry (GCC, 2009 and 2011).

Figure 9. Losses of energy for a typical light duty vehicle (%)



Source: US DoE, 2012.

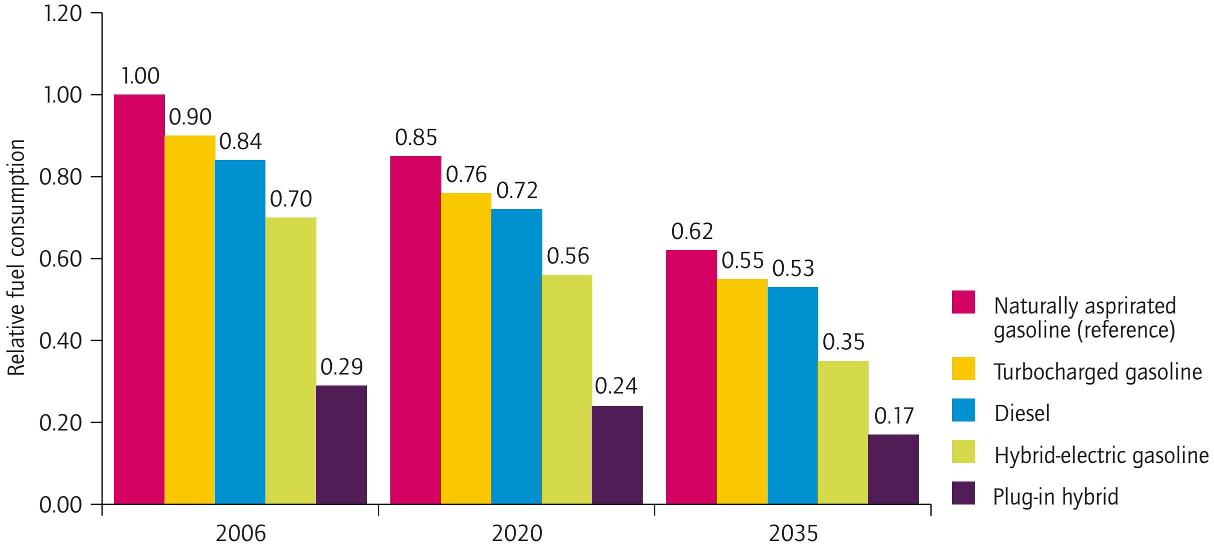
Light-duty vehicles

The technologies available to improve LDV fuel economy include engine, transmission and overall vehicle improvements such as weight, aerodynamics, tyres and auxiliary power systems (lights, heating, air conditioning, etc.).

Compared with 2006, the technology is available for conventional gasoline engine vehicles to be 15% more efficient by 2020; diesels 28% more efficient and full-hybrid vehicles 44% more efficient, according to a comprehensive report on fuel economy potential published by the US National Research Council in 2009, which focused on the North American market (Figure 10). By 2035, the improvements are significantly greater, with turbocharged gasoline and diesel engine vehicles both reaching nearly a 50% improvement over today's vehicles, and hybrids reaching 65% lower fuel use per kilometre. Other studies (such as Bandivadekar *et al.*, 2008; TNO, 2011; and ICCT, 2011a) show similar results in the European context. Unfortunately, few studies are available for non-OECD countries.

The GFEI target of a 50% reduction in new LDV energy consumption (in L/100 km) by 2030 appears feasible with existing technologies (GFEI, 2010). The challenge is to bring these technologies more fully into the market and ensure they are used to improve fuel economy rather than, for example, to make vehicles larger, heavier and/or more powerful while holding fuel economy constant.

Figure 10. Potential reduction in fuel consumption of new US LDVs by 2020 and 2035 relative to 2006 using different power train types



Source: compiled from Cheah, L. *et al.*, 2008.

Gasoline and diesel engines

Most of today's ICE vehicles use petroleum gasoline or diesel fuel, with the two types of engine (spark-ignition for gasoline, LPG and natural gas, and compression-ignition for diesel fuel) operating differently, and with different efficiencies. Diesel engines on average are 25% to 30% more efficient for a similar vehicle.

Although the efficiency of both gasoline and diesel engines improved significantly in the past decade, the IEA estimated in 2009 that a further improvement of about 25%, compared with average performance in 2005, could be achieved with technologies already commercially available.

As of 2012, some of this improvement has already occurred, but around 35% to 50% of the potential – depending on the country – still remains. The emergence of new technologies has changed this picture.

The cost of improving gasoline (spark ignition) engine efficiency by 25% is estimated to be about USD 1 000 per vehicle, while diesel (compression ignition) engines are slightly more expensive to improve due to their already high efficiency (Table 4). These cumulative figures take into account interactions between technologies. They also include the fuel economy and cost penalties associated with systems aimed at reducing pollutant emissions.

Table 4. Estimated tested fuel economy improvement potential and costs relative to a 2005 vehicle

	Improvement potential (% reduction in fuel use)	***Cost (EUR/vehicle)***
	Gasoline engines	
Low friction design and materials	2%	35
Tyres: low rolling resistance	3%	35
Aerodynamics improvement	2%	50
Reduced driveline friction	1%	50
Lightweight components other than BIW	2%	50

Table 4. Estimated tested fuel economy improvement potential and costs relative to a 2005 vehicle (continued)

	Improvement potential (% reduction in fuel use)	*Cost (EUR/vehicle)*
Thermal management	3%	100
Variable valve actuation and lift	2%	230
Auxiliary systems improvement	5%	350
Thermodynamic cycle improvements	14%	400
Strong downsizing	17%	520
Dual clutch transmission	6%	700
Strong weight reduction	12%	1 000
Cumulative before full hybridisation	**51%**	**3 520**
Full hybrid: electric drive	25%	2 750
Cumulative after full hybridisation	**63%**	**6 270**
Diesel engines		
Tyres: low rolling resistance	3%	35
Reduced driveline friction	2%	50
Combustion improvements	4%	50
Aerodynamics improvement	2%	50
Lightweight components other than BIW	2%	100
Thermal management	3%	100
Variable valve actuation and lift	1%	250
Auxiliary systems improvement	6%	440
Strong downsizing	10%	600
Dual clutch transmission	5%	700
Strong weight reduction	10%	1 000
Cumulative before full hybridisation	**39%**	**3 375**
Full hybrid: electric drive	22%	2 750
Cumulative after full hybridisation	**52%**	**6 125**

Sources: IEA analysis based on IEA, 2009; US EPA, 2011; TNO, 2011; ICCT, 2011a.

Note: Technology improvement potential and cost are assumed to be as of today, using devices already commercially available. The cumulative improvement potentials are not the sum of the individual technology improvement potential.

Electric-hybrid vehicles

The development of ICE-electric hybrid vehicles was an important breakthrough for the efficiency of ICE systems. They combine the engine with a motor powered by batteries. The engine can be used just to recharge the batteries (series hybrids), directly to the drive train (parallel hybrids) or in a combination of both (power-split hybrids). Either way, hybrid configurations consume significantly less fuel than conventional ICE vehicles because they allow the engine to be downsized and run more optimally. The electric motor takes over in conditions where the ICE would perform inefficiently, such as at very low speeds or peak power loads. Additional energy savings can come from recovering energy during braking and shutting the engine off in congested traffic and at idle. There are other types of hybridisation, which are ranked according to the power output capability of its motor, from the micro hybrid to the full hybrid (Table 5).

A typical spark ignition, gasoline-powered electric hybrid car commercially available today delivers fuel economy improvements of around 25% to 30% compared with 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.

Complete hybridisation of the LDV fleet appears unlikely, given the higher cost of the hybrid drive-train (Table 4); but it is reasonable to expect that before 2030, a large share of cars and SUVs could be shifted to a hybrid system. Since hybrid systems can encompass many of the other technologies outlined here, they are likely to be included in a fully optimised ICE vehicle that reaches or exceeds the target 50% improvement in fuel economy compared with 2005 vehicles, and play a significant role in a 50% overall worldwide average improvement of new LDVs by 2030. Such hybrid systems, incorporating other improvements already outlined above for gasoline and diesel vehicles, and providing some savings via the opportunity to eliminate or downsize some components, can be expected to have a premium cost of around USD 3 000 for gasoline and diesel powertrains.

Table 5. Hybrid classification

	Hybrid type		
	Micro	***Mild***	***Full***
Capabilities	Stop and start Regenerative breaking	Power assistance Regenerative breaking	All modes
Able to run on electricity only	No	No (or very limited)	Yes
Electric motor share of power train total power	0% to 10%	5% to 30%	>20%
Typical models	Fiat 500 BMW 1-series	Honda Insight Mercedes S class	Toyota Prius

Non-engine technologies

Apart from engines and drive-train systems, a range of important vehicle technologies could help improve vehicle efficiency by lowering the energy demands on the drive train (Table 6).

Aerodynamic drag reduction

Streamlining a vehicle tends to cut wind resistance and drag, particularly at high speeds. 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 under-body panels) requires investment in design and styling, but these are unlikely to be significant in terms of costs per vehicle. Overall, the slow but ongoing trend of improving aerodynamics that has occurred in recent years should continue at relatively low incremental cost per unit of energy savings.

Tyres

Tyre rolling resistance (RR) relates to flattening and friction of the tyre as it rolls. Apart from the effect of inflation (higher inflation results in less flattening), some tyre materials and designs naturally result in lower resistance. New cars tend to come with tyres with fairly low RR, since the manufacturers benefit from this in fuel economy tests. However, in the aftermarket for tyre replacement, many tyres have much higher RR. Improvements in RR to best practice levels 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 are also being introduced at a cost of around USD 20 to USD 30 per vehicle; the only change they 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 a 5% fuel economy improvement potential estimated for tyres is around USD 40 to USD 70 per vehicle.

Head lamps

Most vehicles are equipped with halogen headlamps, but these are relatively inefficient. Light-emitting diode (LED) and xenon lamps are far more efficient but they can be expensive. Xenon lights can match halogen performance with less than half the energy use, but cost several hundred dollars per vehicle. LED lamps still currently cost more than xenon lights but their potential for cost reduction appears to be greater. For use as daytime running lights, LEDs offer significant near-term energy savings at modest cost.

Air conditioning systems

Improved mobile air conditioning (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 a high efficiency MAC system appears to be low, around USD 30 to USD 50 per vehicle. MAC systems using CO_2 as refrigerant fluid have lower climate impact from leakage than most other refrigerants but higher incremental costs, probably from USD 100 to USD 200, mainly because CO_2 needs to be operated at a higher pressure.

Material substitution

Much discussion has focused on the use of aluminium and plastics in vehicles, along with fibreglass, carbon fibre, etc, but most vehicles still rely heavily on steel for strength and safety, in the frame and many components. Stronger, lighter steels have been developed that can play an important near-term role in reducing weight. A significant share of high-strength steel could reduce vehicle weight by up to 10% (Lotus Engineering, 2010). The cost of such reductions has been estimated at below USD 300 per vehicle. Other materials, including aluminium, also have significant lightweight potential and are already in use in some larger, luxury vehicles. Aluminium could cut vehicle weights by 10% at reasonable cost and up to 25% when used in all suitable components, though achieving this full potential could cost well over USD 1 000 per vehicle. Composite materials consisting of a glass- or carbon fibre-reinforced polymer could reduce vehicle weight by up to 40% but could cost up to USD 20 000 per vehicle, so they are a long-term option, needing greater cost reduction before significant applications are seen.

Table 6. Fuel economy potential and cost from non-engine improvements

	FE improvement potential	*Cost to achieve potential*
Aerodynamic drag reduction	3% (more for SUVs)	Low; part of vehicle design phase
Tyres	3% to 5%	USD 40 to USD 70
Head lamps (halogen, xenon, LEDs)	0.2% to 0.5%	USD 300 to USD 500 (provides other benefits, such as visibility improvements)
Air conditioning systems	2% to 4% (more in hot regions)	USD 100 to USD 200
Material substitution and lightweighting	10% weight reduction at little cost premium	USD 1 200 to USD 1 500 per vehicle for 20% weight reduction (Lotus Engineering, 2010)

LDV fuel economy improvement potential, cost and cost-effectiveness

Overall, based on IEA estimates, available technologies could improve fuel economy before 2030 by over 30% for conventional vehicles and 50% for hybrid vehicles (consistent with NRC, 2010b). Though the cost of such fuel economy improvements is uncertain, these targets may be possible for less than USD 3 000 per vehicle without hybridisation and USD 4 000 for a full hybrid. The potential should increase as costs for various components decline over the coming decade. Such technologies, though expensive, do provide considerable fuel savings, which is valuable to both the owner of the vehicle and to society (for example through increased energy security and lower GHG emissions). An advanced hybrid vehicle uses half as much fuel as a base 2005 vehicle, over the life of the car. But is the extra cost of USD 4 000 per car worthwhile? The answer will vary from buyer to buyer, depending on their personal discount rate (since fuel savings occur over the 10- to 15-year period during the life of the car) and the amount and type of driving they do. From the societal viewpoint, the conclusions are easier to draw. The market does not do a good job of delivering these fuel efficiency improvements. But since the societal benefits are so clear, it makes sense for governments to promote or require vehicles to become more efficient.

A comparison of selected technologies – some already extremely cost-effective (such as low RR tyres), others less so (complete advanced hybrid vehicle package) – shows that fuel savings often outpace cost premiums when purchasing the vehicles (Table 7). Fuel savings for individuals include an assumed oil price of USD 120 per barrel and a tax of USD 0.3 per litre and for society include just the resource cost of the oil, without tax. For the individual case, the payback period is the number of years for the individual to recoup the cost of the technology from fuel savings. The societal case, using a 3% discount rate, shows the net cost (or benefit) of the technology over a 10-year period, roughly the life of the car.

The payback period varies considerably, with over five years required for the advanced gasoline engine and advanced hybrid vehicle – probably longer than many drivers are willing to pay (or at least not good enough for them to really consider it as a cost savings strategy). Yet for all these technologies, the societal cost is net negative – that is, the fuel savings over 12 years (slightly discounted) are far more valuable than the cost of the technology. This means that the CO_2 saved, more than 17 t over the life of the advanced hybrid, comes at a net negative cost – *i.e.* a cost per tonne well below USD 0. This is a robust finding, and holds across a reasonable range of assumptions regarding fuel prices, travel distances, etc.

Table 7. Cost and fuel savings benefit calculations for selected technologies

	Technology cost (USD)	Fuel economy improvement		Value of fuel savings per year (USD)		Individual payback period	Societal net present value (3%) (USD)	CO_2 saved over vehicle life (tonnes)	Net CO_2 reduction cost (USD per tonne)
		%	L/ 100 km	Individual	Societal				
Low RR tyres	70	4%	0.3	63	48	1.1	341	1.4	-247
More efficient air conditioning	150	3%	0.2	47	36	3.2	159	1.0	-153
Advanced gasoline engine	2 150	28%	2.2	438	338	4.9	730	9.7	-75
Advanced hybrid vehicle	4 000	50%	4.0	783	603	5.1	1 142	17.3	-66

Notes: cars are assumed to be driven an average of 15 000 km (9 000 miles) per year for 10 years, or 150 000 km (93 000 miles) over vehicle life, before discounting. Fuel retail cost is assumed to be USD 1/L untaxed (related to USD 120 per barrel oil price), and USD 1.3/L with tax. This is much lower than current European prices but higher than prices in many other countries. Base vehicle is assumed to consume 8 L/100 km (about 30 mpg).

Heavy-duty vehicles

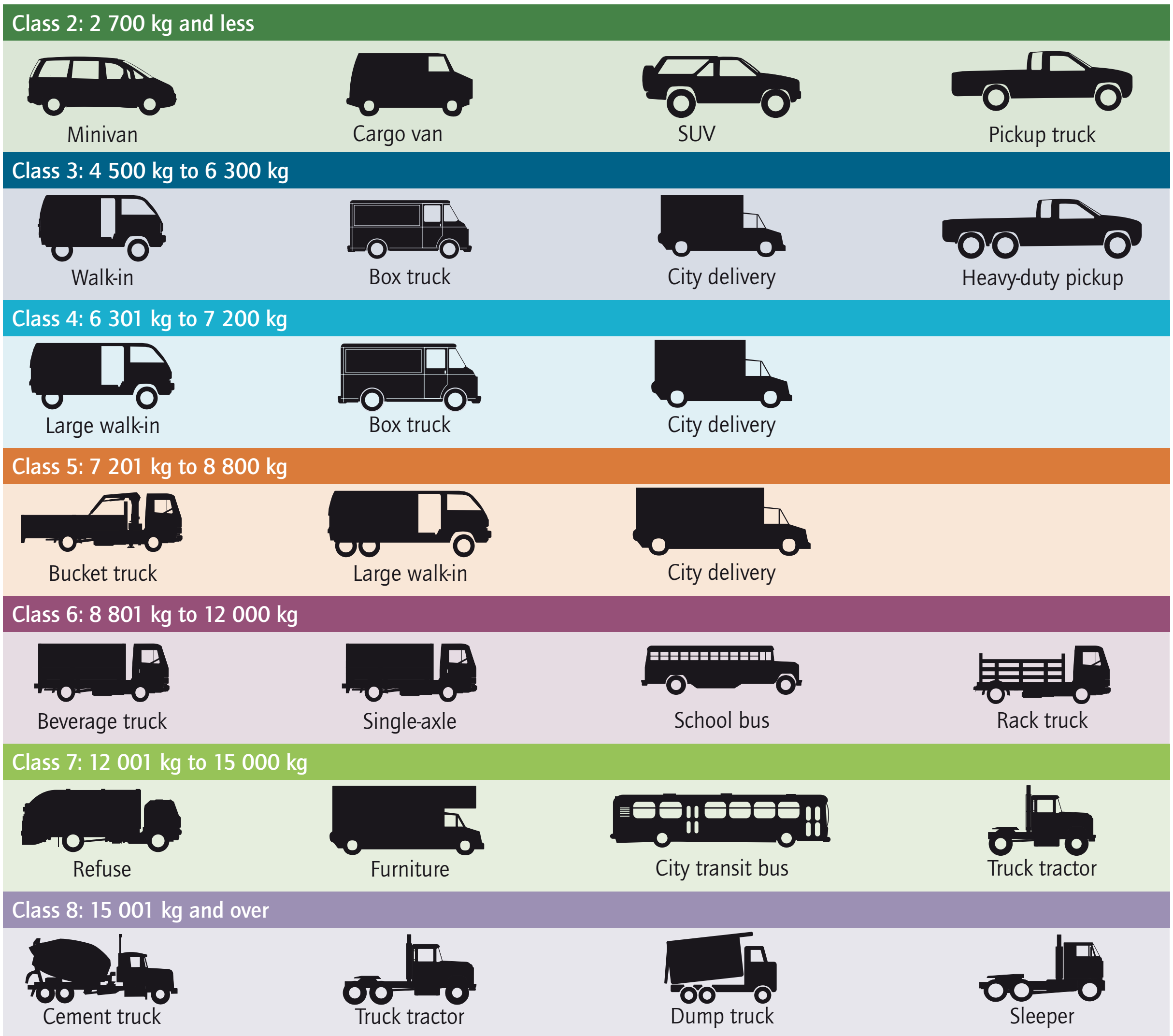
Truck and buses have similar platforms and engines, so although imminent fuel economy standards for heavy vehicles tend to focus on heavy freight vehicles, they could also easily be applied to buses, as is already the case in the United States, Japan and for intercity buses (coaches) in China.

Heavy vehicle efficiency relies on many of the same principles as for cars, but different technologies are often more appropriate for the size, weight and purpose of heavy vehicles. A broad variety of types of light-, medium- and heavy-duty vehicles, with countless specifications, fulfil different transport needs, which all have an impact on fuel economy.

Some aggregation of the technologies and vehicle types is necessary to manage analysis and policy making for these vehicles.

Commercial vehicles are classified by gross weight. In the United States, HDVs start with Class 2 excluding minivans (Figure 11). In Europe, all commercial vehicles with a gross weight above 3.5 t are classified as HDVs. Truck-trailer combinations represent the largest single share of on-road freight activity (on a tonne-km basis) in many regions of the world. Today, more trailers than trucks exist, the ratio depending on the region. Trailers often have separate owners from trucks. If trailer owners do not need to pay for the fuel bill they have no incentive to take fuel economy into account, affecting significantly the

Figure 11. HDV classification according to gross weight, United States



Source: US DoE, 2011.

truck-trailer system fuel efficiency. This market failure needs to be addressed, for example by requiring labelling of trailers or standardisation of the entire truck-trailer combination to reduce gaps and frontal air exposure. Refining current standards on size and length would be a first step to address inconsistencies and counter-acting regulation.

Technological measures to improve fuel efficiency for heavy vehicles can be split into four categories:

- engine: including auxiliary aggregates such as cooling, power steering and the braking system;
- drive-train: transmission, including any hybridisation system;
- vehicle: chassis, bodywork (including fairings and other aerodynamic devices), trailer and tyres; and
- ITS/ICT: intelligent transport systems and information/communication technologies to help drivers optimise in-use fuel economy.

Fuel savings and the impacts of technologies are highly dependent on whether the truck is mainly used for urban driving (such as delivery trucks) or long-haul (mainly highway) shipments (Table 8).

Urban and regional delivery services are dominated by small and medium freight trucks, typically up to a gross weight of 16 t; long-haul trucking is mostly carried out with large, often articulated trucks (tractor/cab and trailer) up to a gross weight of 40 t, depending mainly on each country's weight limits. Urban and regional delivery is characterised by lower average speeds, frequent acceleration and deceleration, and frequent stops. In these conditions, fuel savings can be optimised by improving engine and drive-train efficiency and introducing technologies such as "idle-off" and hybridisation. Long-haul services are mostly carried out at high and fairly constant speeds, so improving aerodynamics and reducing RR are key measures. Some key technologies are described below. Many are already commercially available or will be within the next five to ten years.

Table 8. Truck fuel economy improvement technology matrix

Category	Technology	Fuel improvement potential	Technology cost range (USD)	Market-ready
Engine	Variable valve actuation	1% to 2%	300 to 600	✓
Engine	Sequential turbo/downsizing	Up to 5%	NA	✓
Engine	Speed control (injection)	Up to 5%	NA	✓
Engine	Oil and water pump with variable speed	1% to 4%	NA	✓
Engine	Controllable air compressor	3.5%	~200	✓
Engine	Smart alternator, battery sensor electric accessory drive	2% to 10%	NA	✓
Engine	Start/stop automatic	5% to 10%	600 to 900	✓
Engine	Dual fuel systems	10% to 20%	~33 000	✓
Engine	Pneumatic booster: air hybrid	Up to 4%	800 to 1 000	
Engine	Turbocompound (mechanical/electric)	4%/7%	~3 000/8 000	✓
Engine	Bottoming cycles/waste heat recovery (*e.g.* organic Rankine)	1.5% to 10%	15 000 to 16 000	

Table 8. Truck fuel economy improvement technology matrix (continued)

Category	Technology	Fuel improvement potential	Technology cost range (USD)	Market-ready
Drive train	Eco roll freewheel function	1%	NA	✓
Drive train	Automated manual transmission	4% to 6%	4 500 to 6 000	✓
Drive train	Full hybrid	15% to 30% urban 4% to 10% long haul	30 000 to 33 000	✓
Drive train	Flywheel hybrid	15% to 22% urban 5% to 15% long haul	~4 500	
Drive train	Hydraulic hybrid	12% to 25% urban Avg 12% long haul	~13 000	
Vehicle	Low rolling resistance tyres	5%	300 to 500	✓
Vehicle	Aerodynamic fairings	0.5% to 5%	1 500 to 1 700	✓
Vehicle	Aerodynamic trailer/boat tail	12% to 15%	4 500 to 5 000	✓
Vehicle	Single wide tyres	5% to 10%	~1 700	✓
Vehicle	Light-weight materials	2% to 5%	~2 000 to 5 000	✓
Vehicle	Active aerodynamics	Up to 5%	~1 600	
ITS/ICT	Predictive cruise control	2% to 5%	~1 900	
ITS/ICT	Driver support system	5% to 10%	NA	✓
ITS/ICT	Acceleration control	Up to 6%	NA	✓
ITS/ICT	Vehicle platooning	Up to 20%	NA	

Notes: red = short-haul, medium freight trucks; green = long-haul, heavy-duty trucks; black = all truck types.
NA = not applicable.
Sources: IEA, 2010a; Hill *et al.*, 2011; Cooper *et al.*, 2009; Duleep, 2011; Law, K. *et al.*, 2011; NRC, 2010a.

Enhanced engine design: optimising the processes

Enhanced engine design offers a wide range of ways to reduce fuel consumption. Some lower-cost technologies already applied in passenger light-duty diesel vehicles can be adopted for HDVs, including variable valve actuation (VVA) and engine downsizing in combination with sequential turbo charging. VVA can improve fuel economy by around 1% for long-haul road transport, for around USD 600 (near term) to USD 300 (long term) per vehicle, thanks to the learning effect and economies of scale (Cooper *et al.*, 2009).

As for LDVs, automatic start-stop systems that prevent idling are a low-cost option (about USD 800) that can improve fuel efficiency in urban delivery trucks. They are only suitable if no further electricity is needed (*e.g.* for refrigeration) when the vehicle is stopped. Under urban driving conditions, average fuel savings of around 6% can be achieved (Hill *et al.*, 2011).

Turbo-compounding can also reduce fuel consumption of conventional ICEs, especially in heavy-duty, long-haul vehicles. A turbo-compounded diesel engine consists of a turbo-charged engine plus an additional velocity turbine placed in the exhaust gas stream after the turbo charger. The mechanical energy generated by the additional turbine is either coupled to the crankshaft via sophisticated transmission, or powers an electric generator (electric turbo-compound), reducing the power needed from the ICE, allowing for a displacement reduction (downsizing). Together with a starter generator, an electric turbo-compound engine also allows for regenerative braking, in which the electricity generated during braking is stored in batteries. Altogether, electrical turbo-compound units can reduce fuel consumption by up to 8% in long-haul trucks (Hill *et al.*, 2011) at significantly lower costs than hybridisation. Hybridisation and electrical turbo compounding can also be used simultaneously.

Waste heat recovery, applying bottoming cycles (*e.g.* the organic Rankine cycle), marks the upper end of conventional diesel ICE optimisation, and can improve fuel economy by up to 10%. This comes at the cost of adding complexity to the engine system: heat from the exhaust is used to evaporate an organic fluid at high pressures and then expand it using a turbine. The expanded working fluid is condensed and compressed before entering the boiler again. A generator transforms the mechanical energy into electricity that can then be used to power auxiliaries or assist the engine. Lowering the exhaust gas temperature might nonetheless be counterproductive for catalytic converters and other exhaust gas treatment devices that usually need high temperatures.

Drive-train: automation and hybridisation

Automated manual transmission has gained market share since the 1980s in Western Europe, where almost all new HDVs are now equipped with it, so its application as a new fuel economy measure mainly relates to the United States, where most long-haul HDVs are still equipped with manual transmission. Automated manual transmission combines advantages of a manual gear shift, such as high efficiency, with those of automatic transmissions, such as the ability to change gears at the best point and provide comfort to the driver. Especially in fleets with differently skilled drivers, fuel use can be reduced by up to 10% at medium costs around USD 4 500 (Hill *et al.*, 2011). The use of a freewheeling function ("EcoRoll") in combination with predictive cruise control can further improve fuel economy by up to 6% (Hill *et al.*, 2011).

Hybridising the drive-train to recover brake energy can improve fuel economy by up to 20% under urban driving conditions. The underlying principle is the same as for LDVs: parallel hybridisation combines an electric generator/motor with a conventional diesel ICE and battery storage. If an ICE and electric motor are coupled in series, operating the ICE under optimal conditions can achieve additional savings at the cost of using a larger electric motor. Fuel use can decrease by around 6% for long-haul Class 8 HDVs (Cooper *et al.*, 2009) and up to 30% for medium freight trucks under transient (stop-and-go) traffic conditions, *e.g.* urban delivery. Over the vehicle lifetime, total costs can be lower for hybrid long-haul trucks than for conventional trucks, and payback times as short as four years can be achieved for buses and six years for long-haul trucks (Hill *et al.*, 2011). The greatest efficiency gains can be reached under transient conditions.

Truck design: lower tyre rolling resistance and better aerodynamics

Reducing aerodynamic drag and rolling resistance has more impact at higher speeds and is thus especially cost effective for long-haul vehicles.

Low rolling resistance tyres can improve fuel economy by up to 5% at little or no additional cost. The use of single wide tyres instead of double rims and tyres on all respective axles could reduce fuel consumption by up to 10%, depending on the number of axles (Cooper *et al.*, 2009).

Improving aerodynamics can reduce fuel consumption by up to 8%, starting with simple fairings, aiming at smoothing the airflow over tanks, around the bumper and over the cabin, and at reducing the gap between tractor and trailer (Cooper *et al.*, 2009). Improving trailer design using side skirt fairings, rounded edges, more elaborate under-body wedges and rear fairings ("boat tail") can improve fuel economy by around 10% on average (Hill *et al.*, 2011).

Reducing the weight of the HDV itself has two effects on fuel economy. For weight-restricted applications (*i.e.* when the amount of cargo transported is limited by the allowed payload) the ratio of payload per other truck weight can increase, and fuel use per payload unit therefore declines. For volume-restricted applications (*e.g.* transporting a truck full of potato chips) and highly transient driving cycles, additional cargo cannot be added, but fuel consumption can be reduced as a function of weight reduction, with a 10% reduction in weight yielding up to 4% in fuel savings (Hill *et al.*, 2011). One simple way of reducing weight is the use of single wide tyres and aluminium rims.

ITS/ICT: driver support

As for cars, the actual in-use fuel economy of trucks depends not only on vehicle technologies but also on road conditions and driving behaviour. Intelligent transport systems and information/communication technologies are being applied at two different levels: optimisation of individual driving style and avoiding congestion.[3]

3 Routing and logistics management can also play a big role in saving fuel but is outside the scope of this roadmap.

Box 7. Heavy-duty vehicle fuel economy: Europe versus United States

The average fuel consumption per kilometre of long-haul (semi-trailer) trucks in the United States differs significantly from that in Europe. In the United States, the average truck consumes around 36 L/100 km to 40 L/100 km at 75% load capacity for a long-haul driving cycle (Cooper *et al.*, 2009; Law *et al.*, 2011). In Europe, fuel economy estimates vary between 30 L/100 km and 35 L/100 km (Hill *et al.*, 2011; Law, K. *et al.*, 2011). Although aerodynamic drag of a modern US long-nose tractor is less than for a modern European cab-over, this advantage is reversed by higher weight, one additional axle, higher power and manual transmission. Higher speeds and a bigger gap between tractor and trailer also lead to higher fuel consumption in the United States. Considering that the gross vehicle weight for US trucks on interstate highways is limited to 36 t (80 000 lb), their efficiency per tonne is notably lower.

Acceleration control, speed control, green zone indicators and predictive cruise control can help the driver to keep the engine at best load points and prevent unnecessary acceleration and deceleration, saving 2% to 10% of fuel. Vehicle platooning – in which trucks reduce wind drag by driving in line – has great potential for saving fuel but also considerable road safety drawbacks.

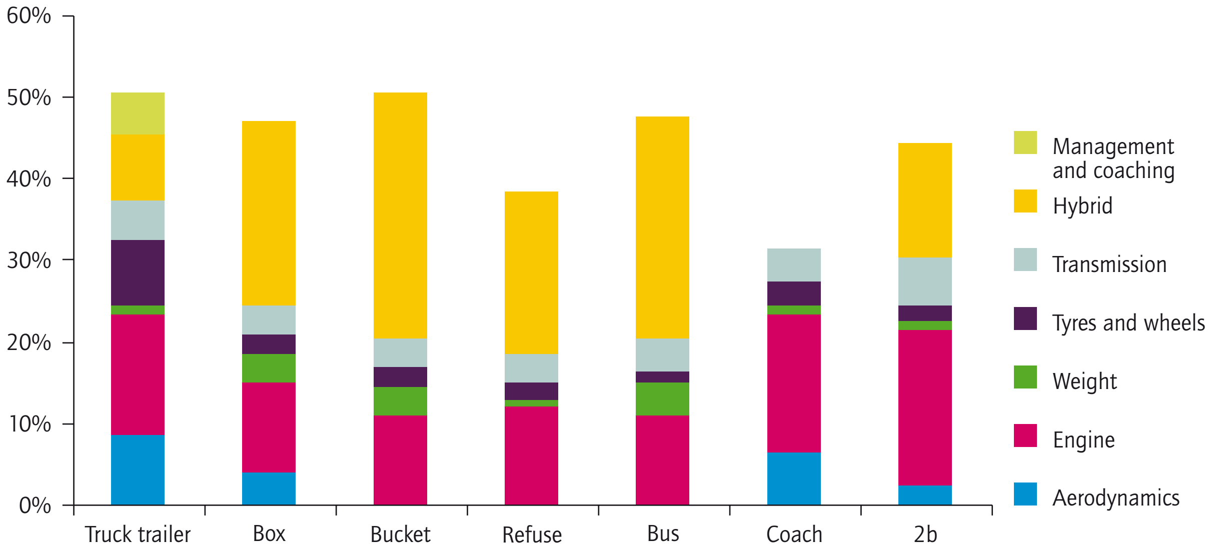
Overall potential improvement and cost-effectiveness of truck technology measures

As with cars, the combined fuel economy benefit of different truck technologies is not necessarily additive. Nonetheless, combining progressive engine, vehicle, drive-train and ITS technologies can improve fuel economy by 30% to 50% in today's trucks. The overall potential and relative contribution of different types of technologies depends heavily on the type of truck (Figure 12). Tyres and wheels as well as aerodynamic improvement have the most effect on high-speed, long-haul vehicles and coaches. Hybridisation is especially valuable for short-haul vehicles driving under urban conditions with very transient cycles.

The use of bigger, longer trucks with higher payload capacities can significantly improve fuel economy; this issue is regulatory, logistical but not technical. It is outside the scope of the technology roadmap but is mentioned here as a potential source of fuel use reduction. On the basis of tonnes transported, simply increasing payload by 30% leads to about 15% less fuel consumed per tonne (when running with full payload). The added value of scaling up the vehicle gets smaller when other truck technologies to reduce fuel consumption are applied at the same time, and there are limits to this strategy (mainly related to safety concerns).

In terms of cost effectiveness, technologies to increase fuel economy for different truck types and buses in Europe have a wide range of payback times (Table 9). Start-stop systems are cost effective, showing payback times around one to two years for most heavy commercial vehicles. Engine technologies like electrical turbo compound or heat recovery systems are only effective at high annual mileages, which is only on the case for long-haul vehicles. Flywheel hybrid systems seem to be especially effective in city buses, as they can profit from stored energy in frequent start-stop situations. Technologies with a higher payback time – greater than two or three years, but still less than the vehicle lifetime of up to ten years – offer a large potential for fuel savings and hence CO_2 reductions, but most will not be significantly used without the introduction of regulatory approaches.

Figure 12. Relative contribution toward fuel economy improvement by truck/bus type and technology type for the United States



Note: 2b are mid-size vans and pick-ups as defined in Figure 11.

Source:NRC, 2010a.

Table 9. Estimated payback time for selected technologies according to vehicle type (years)

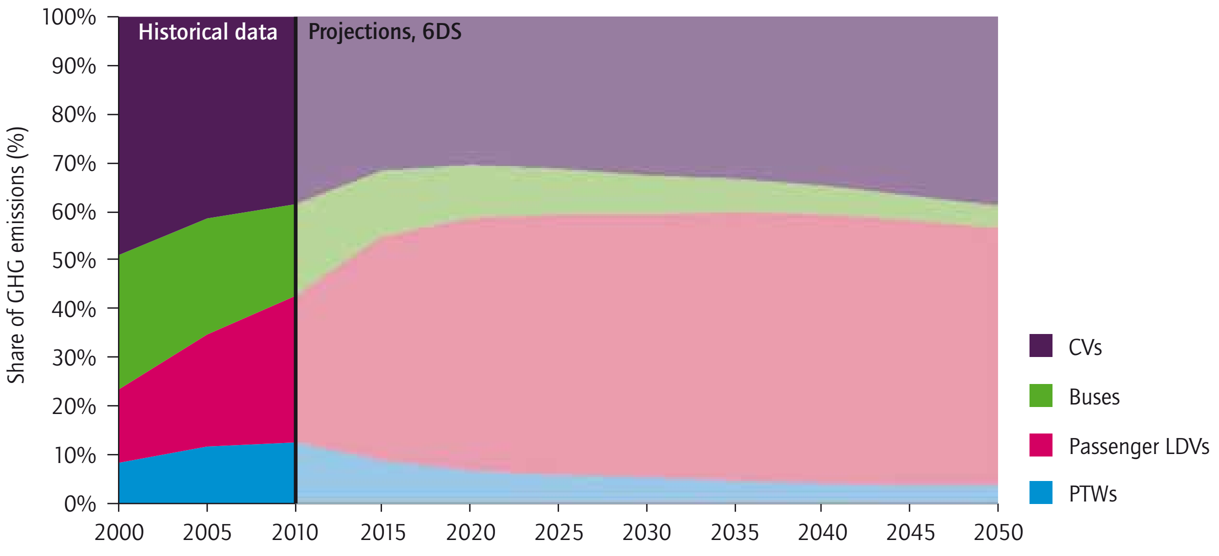
Technology	Service delivery	Urban delivery	Municipal utility	Regional delivery	Long haul	Bus	Coach
Pneumatic booster	9	6	4	4	0.6		4
Electrical turbocompound	125	83	51	19	6	39	19
Heat recovery	140	92	56	31	6	43	32
Automated transmission	13	8	5	15	8	4	16
Start-stop system	2	1	1	1	2	1	2
Full hybrid	21	14	9	16	6	4	17
Electric vehicle	19	13	8	7		6	8
Flywheel hybrid	4	3	2	3	3	1	3
Single wide tyres	4	3	2	1	1	1	1
Aerodynamic trailer				2	1		
Aerodynamic fairings				1	0.5		
Dual fuel	15	10	6	6	2	3	6

Source: Hill *et al.*, 2011.

Powered two-wheelers

Improving the fuel economy of powered two-wheelers (PTWs), including scooters and motorcycles, has not been of great interest because they use relatively little fuel – both per vehicle and overall (in most countries). Fuel use and CO_2 emissions of PTWs represent less than 1% of the total for the road transport sector in all OECD countries. However, in some developing countries PTWs represent a significant share of the vehicle stock and travel. This is especially true in India, China and South-east Asian countries; across Asia, the IEA estimates that PTWs emitted 13% of road transport CO_2 in 2010 (Figure 13). This share is high enough that in such countries it could be very important to push for fuel economy improvements in such vehicles over the next 10 to 20 years. However, the potential for improvement in this area is predicted to decrease gradually as GDP per capita increases and citizens trade their PTWs for cars, as is occurring now in China.

Figure 13. Share of WTW GHG emissions of the road transport sector for Asia, by mode, 2000-50



Technology potential to improve powered two-wheeler fuel economy

In most regions, the main PTW regulatory focus in recent years has been on safety and reducing pollutant emissions. Although this is likely to continue, the technologies needed to cut pollutant emissions can also save fuel, though some measures can increase fuel use. An important emissions and noise reduction strategy has been to convert from two-stroke engines to four-stroke. Modern four-strokes can also yield efficiency benefits, mainly thanks to technology and knowledge transfer from the automotive industry. Even though the two-stroke theoretical thermodynamic cycle remains more energy-efficient than the four-stroke cycle, lack of development has prevented this type of engine from performing well enough to meet noise and pollutant emissions standards at low cost.

The uptake of electronic fuel injection systems also benefits both pollutant control and fuel economy. But, as is true for cars and trucks, PTW pollution treatment systems (such as exhaust catalysts) create higher backpressure, decreasing the efficiency of the combustion cycle. Overall, fuel economy could be improved by 20% to 40%, primarily through engine technologies, even with the use of catalytic converters (ICCT, 2011a).

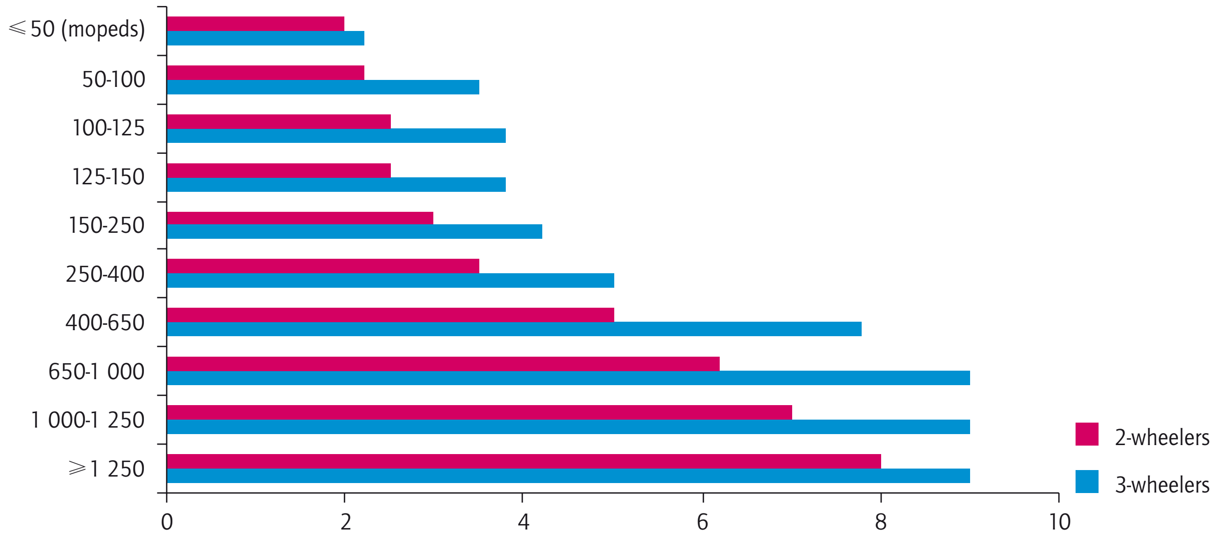
New technologies are usually adopted first by the automobile industry and only penetrate the PTW market once costs have been significantly reduced thanks to the learning effect and economies of scale. Recent examples include fuel injection systems, emissions after-treatment systems and anti-lock brakes.

Taking this tendency into account, power train efficiency technologies that could soon enter the motorcycle mass market include direct

Table 10. Technology pathways for powered two-wheelers

	Urban PTWs (<200 cc)	Highway PTWs (>200 cc)
Mid-term technology options	Four-stroke, biofuel compatibility, human-electric hybrids	Direct injection, VVT, biofuel compatibility
Long-term technology options	Full electrification, human-electric hybrids	Engine downsizing with low boost turbocharger, ICE-electric hybrids

Figure 14. Two- and three-wheeler fuel consumption per 100 km, by engine power category



injection engines and related technologies such as variable valve timing; greater use of lightweight components such as high-strength steel; and more efficient head lamps. ICE-electric hybridisation seems likely to struggle to gain a foothold, mainly because fuel savings are typically too low to pay for the cost of hybridisation. For small PTWs, full electrification is probably more likely to succeed in the near term, and is already in use in millions of electric bicycles in Asia (particularly in China). Electric two-wheelers (with or without pedal assist) also may gain acceptance in developed countries in the coming years. These are highly efficient vehicles that also shift the energy source to electricity (the impacts of which, in terms of electricity CO_2 intensity and related issues, are beyond the scope of this roadmap but are discussed in the IEA EV roadmap).

The possible technology pathways that PTWs might follow according to size and application depend on the type of use (Table 10).

To date, only China has implemented fuel economy standards for two- or three-wheelers (ICCT, 2011b). Current fuel economy standards become more demanding as engine size decreases (Figure 14). The much higher allowed fuel consumption for larger, more powerful PTWS reflects the impact of weight and power, and indicates that efforts to avoid significant upsizing of these vehicles could save significant amounts of fuel.

In-use fuel economy: technologies and measures

Many factors that have significant impacts on fuel economy are not taken into account by official tested fuel economy figures. Improving actual fuel economy on the road requires a range of measures outside the test lab, apart from how vehicles are designed and built (though paying more attention to actual in-use fuel economy could help manufacturers improve vehicles in this regard). This section covers trends as well as potential technologies and measures for improving in-use vehicle efficiency.

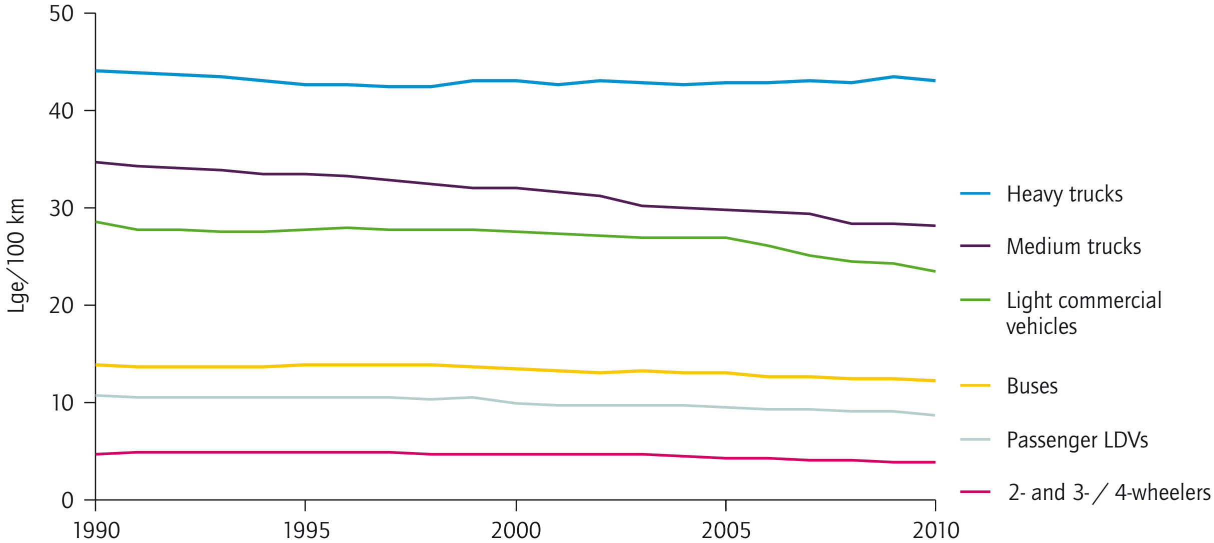
Trends in average in-use fuel economy across the vehicle stock

The fuel economy of the entire stock of vehicles, in actual on-road conditions, depends on many factors and is difficult to measure. The tested fuel economy of new vehicles is a good indicator of their performance in-use, but is likely to underestimate fuel consumption per kilometre, since it is difficult for tests to capture all the factors that can reduce fuel economy on the road.

For each country or region, the IEA calculates vehicle stock fuel economy by linking official IEA statistics on fuel use to the MoMo database on road vehicles stock and utilisation using the PUCE methodology (Box 2). To conform to the PUCE identity, the stock average fuel economy must equal total vehicle travel divided by total vehicle fuel use (or vice versa, depending on fuel economy units). This ratio is typically used by the IEA to estimate in-use fuel economy. When available, official sources on stock-average fuel economy have been used, which generally have proven to be close to IEA estimates.

The results show that average stock on-road fuel economy of different types of road vehicles has improved over the years (Figure 15). Separate breakdowns (not shown) suggest that fuel economy has improved a bit faster in non-OECD countries than in OECD countries, albeit from a higher starting point in 1990. Vehicles' average age and road conditions are the main factors that keep average fuel economy lower in non-OECD countries. However, vehicle average size and embedded technologies also play an important role for the average on-road fuel economy. Isolating the exact impact of each factor is difficult because of limited data.

Figure 15. Worldwide stock average on-road fuel economy by mode, 1990-2010



Source: IEA, 2012c.

Factors affecting in-use fuel economy

The difference between tested and in-use fuel economy is due to attributes of the vehicle, the driver and the road (Table 11). Creating policies and measures to address all these elements is often referred to as the "integrated approach" (see next section).

Table 11. Factors affecting in-use fuel economy

Factor	*Effect*
Vehicle condition	Poor maintenance of engine (particularly for older cars), under-inflation of tyres, tyre misalignment, unnecessary weight on or in vehicle (*e.g.* ski racks), etc., can reduce fuel economy.
Average speed (and traffic congestion)	Vehicle fuel economy can vary considerably with average speed. It is typically optimal between 50 and 90 kilometres per hour (km/h), and deteriorates rapidly above 120 km/h (due to wind resistance) and at low speeds with stop-and-go driving.
Road surface	Since tyres' rolling resistance (RR) can have a significant impact on fuel economy, pavement quality helps, along with low RR, well-inflated tyres.
Driver behaviour	Eco-driving (including avoiding rapid starts and stops, and early shifting for manual transmission cars) could improve average fuel use by 10% or more, and eco-driving training appears to be a very cost-effective way of improving fuel economy. Many fleet operators understand the potential and organise training programmes to encourage or require their drivers to apply driving styles that save fuel.
Auxiliary equipment on vehicles	Several vehicle components are not typically included, or fully reflected, in homologation tests. These include auxiliary energy-using equipment such as air conditioning, heating and lighting (because these are generally turned off during tests). Encouraging more efficient equipment to be adopted may require changes to test procedures, or separate tests and regulations on such equipment.

Apart from vehicle technologies, several other strategies can improve in-use fuel economy, including encouraging fuel-efficient driving behaviour, and improving traffic flow (*e.g.* via reducing congestion, better traffic light management or highway design) and general road conditions.

Both of these involve deploying certain key technologies, and can provide significant fuel savings, so are included in this roadmap.

Driving behaviour

The way a person drives a vehicle – whether a car or a truck – can have a major effect on in-use fuel economy. Many tips can help drivers improve their driving style to save fuel (IEA, 2011c).

On the road

- Start driving as soon as the engine is started (no need to warm up modern engines except in very cold conditions).
- Avoid unnecessary idling.
- Don't speed (as speed rises above 90 km/h, fuel economy can decrease rapidly).
- Use overdrive gears and cruise control when appropriate.
- Minimise the need to brake by anticipating traffic conditions.
- Avoid jackrabbit starts and stops.
- Use the air conditioner only when absolutely necessary (although at high speeds, air conditioning may reduce fuel economy less than opening windows).
- Combine errands into fewer car trips.
- Remove excess weight (*e.g.* remove ski and cycle racks when not in use).
- Avoid packing items on the roof of the car.

At the garage

- Keep the engine tuned.
- Keep the tyres properly inflated and aligned.
- Change oil regularly.
- Be sceptical about any gizmo that promises to improve fuel economy.[4]

4 FTC, 2012.

While improving fuel efficiency by changing driver behaviour is mostly a matter of education and training, technologies are being introduced that can help drivers track fuel economy, often in real time, such as gear-shift indicators, tyre pressure monitor sensors and eco- and/or fuel economy displays. Fuel economy can be improved by up to 10% when adopting eco-driving measures (IEA, 2010b).

Many companies with business fleets (whether of cars or trucks) have systematically trained their drivers in eco-driving, primarily to save money through fuel savings. Such programmes have significant impacts and tend to be very cost effective, especially when oil prices are high. In France, La Poste Group has implemented ongoing training on eco-driving; early test results show a reduction of 8% in CO_2 emissions; at the group scale, that would mean five million litres of fuel saved per year (La Poste, 2007).

Though training programmes can help, many drivers eventually return to their “bad” habits, so regular updates to training and monitoring programmes (for business fleets) can help to ensure the long-term benefits from eco-driving techniques.

Road and traffic conditions

Smoother road surfaces and better traffic flow can improve fuel economy by reducing rolling resistance and stops and starts. Average speed and fluctuations in speed in urban driving conditions – which both depend in part on traffic congestion – have a significant influence on in-use fuel economy (JAMA, 2008). Three main techniques that adjust vehicle speeds can improve fuel economy: congestion mitigation, traffic flow smoothing and speed management (Figure 16).

The fuel savings benefits can be lost, however, when improved traffic flow encourages additional driving, but this can be addressed by managing traffic in other ways, such as via fuel pricing, road pricing and parking availability/pricing.

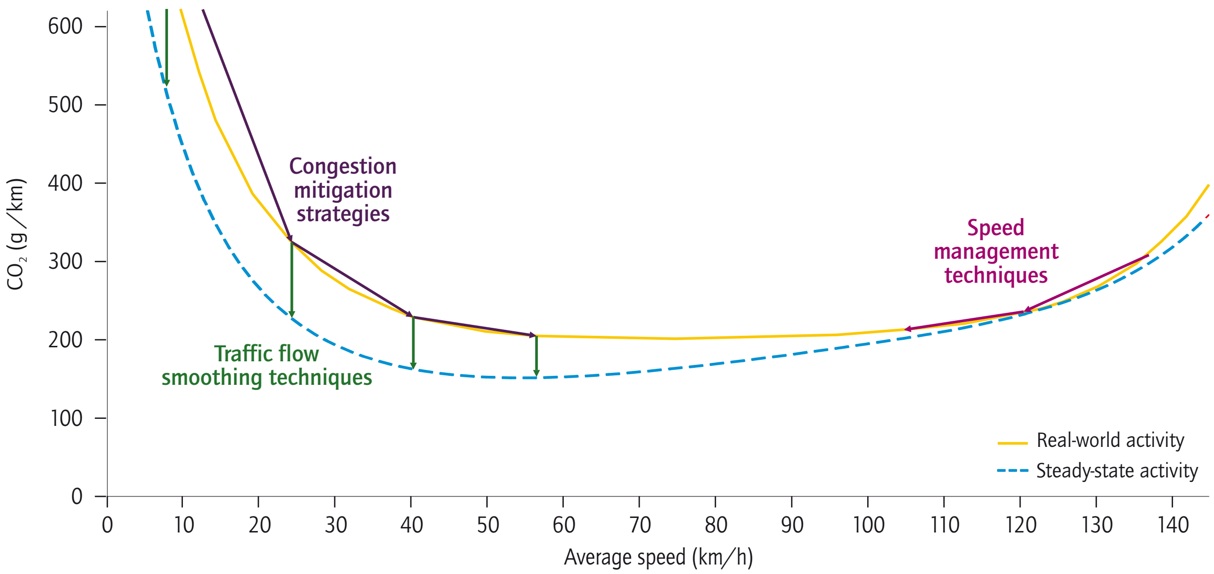
Studies in Sweden, the Netherlands and the United States have shown that smoother roads could improve fuel economy by 5% to 10% (Table 12).

Table 12. Impact of road surface on fuel economy at constant speeds (% improvement)

Study		*Swedish study*		*Dutch study*
Speed (km/h)	50	60	70	90
Dense asphalt 0/8		0		
Dense asphalt 0/16	2.7%	2.4%	-0.5%	0
Porous asphalt 6/16				0%
Stone mastic asphalt 0/6				3.4%
Double-layered porous asphalt 4/8 + 11/16				1.2%
Cement concrete, broomed transversely	3.6%	5.0%	2.7%	0.4%
Cement concrete treated with a surface epoxy durop	3.6%	5.0%	2.7%	2.7%
Brick-layered pavement				5.3%
Surface dressing 4/8	0.1%	3.7%	6.1%	
Surface dressing 12/16	1.9%	7.2%	7.1%	

Source: adapted from EAPA, Eurobitume, 2004.

Figure 16. Possible use of traffic operation strategies in improving on-road fuel economy



Source: Barth and Boriboonsomsin, 2008.

Taking all factors into account: the integrated approach

An integrated approach is needed to improve vehicle fuel economy, with measures focusing on technical improvement of new vehicles and on their in-use performance. The ratio of in-use fuel economy for a given vehicle to its tested results for certification purposes – referred to as the "gap factor" – captures the net effect of all factors affecting fuel economy that are not reflected in the test conditions (JAMA, 2008).

Combining all the factors listed in the previous sections that can improve fuel economy could halve the average on-road fuel use in the coming decades (Table 13).

Better evaluation is needed of the potential energy efficiency advantages of measures focused on drivers and roads. The IEA is willing to launch a project measuring real-life fuel economy with a worldwide scope, in OECD countries and non-OECD countries.

Table 13. Potential fuel economy improvement range by improvement and vehicle type

Factors affecting fuel economy		Fuel economy improvement (%)		
		Cars	PTWs	Trucks
Vehicle	Power train technologies (tested on cycle)	30 to 40	15 to 25	20 to 35
	Other power train/vehicular technologies (incl. auxiliaries)	10 to 20	5 to 10	10 to 20
Driver	Eco-driving	5 to 10	5 to 10	5 to 10
Road	Congestion	5 to 7	2 to 5	5 to 10
	Surface	2 to 7	2 to 7	2 to 7
Total (taking into account non-additivities)		46 to 65	20 to 45	35 to 60

Overcoming the barriers to improving fuel economy

One would expect fuel economy to improve with no need for any external incentive, as the technologies are in many cases available and cost-effective, yet this is hardly happening. While car companies are steadily deploying new technologies in their products, the rate of technology uptake in some cases is slow (*e.g.* hybridisation), and in many cases is used for purposes other than improving fuel economy (*e.g.* increasing engine power while holding fuel economy constant). Several market-related barriers reduce incentives to improve vehicle fuel economy:

- **Low fuel prices:** when oil prices are low, especially in countries and regions with low fuel taxes (or outright subsidies), the economic return to individuals and companies from purchasing fuel-efficient vehicles can be too low to justify the additional up-front cost.
- **Oil price uncertainty:** even when oil prices are high, uncertainty about their future levels (including the unlikely possibility that they may soon drop again) can discourage buyers from purchasing more fuel-efficient vehicles.
- **High discount rates:** many buyers expect the value of a vehicle to fall quickly after purchase – and similarly, demand unrealistically short payback times for investments – even though they plan to keep the vehicle for a relatively long time.
- **Lack of information:** consumers may not know the fuel economy of different vehicles, or trust the information they receive. Labelling with understandable information on fuel economy can help, as well as widespread availability of the labelling and rating information. Improved testing methods that more closely reflect real-world driving conditions (and actual experience) may also be needed.
- **Competition with other attributes:** the addition of a new technology that can save fuel also creates an opportunity for manufacturers to reconfigure the vehicle so that, rather than save fuel, fuel economy remains constant while performance (such as horsepower) is increased. Similarly, vehicles can be made larger (and heavier) at a given fuel economy. If consumers demand these other attributes, fuel economy may not improve even though fuel economy technologies are added to a vehicle.

Table 14. Matrix of barriers versus expected impacts of policies

Barriers	Policy options to address market failure			
	Information and labelling	Fuel economy standards	Fuel taxes	CO_2-based vehicle taxes/feebates
Low and volatile fuel prices; price risk aversion	Provides key info to consumers; more helpful when annual fuel spending are also displayed.	Delivers improved fuel economy regardless of market prices or buyer risk aversion.	Helpful since it raises the fuel cost of driving; can include a price floor mechanism.	Can send strong market signals to buyers; but doesn't address variable (per-km) cost of travel.
High discount rates	Same as above.	Overcomes the market failure by improving the vehicle supply (OEMs) side; requirements across whole fleet can guarantee an outcome.	Can help, but if discount rates are very high, a high tax might be needed to compensate.	Largely overcomes the discount rate issue by reducing cost differential up-front.
Lack of information	Directly addresses this problem but may not fully overcome counter perceptions that fuel economy is unimportant.	Helps improve fuel economy even when consumers are less informed, but should be easier to implement with informed consumers.	Doesn't address information problem; may be more readily accepted and have bigger impact when more information is available.	Must be linked to labelling system so consumers know and understand the basis for the relative taxes.

Policy options

While these barriers can prevent markets from delivering the benefits of fuel economy improvements, several policy options are available that can accelerate the uptake of technologies and ensure that they are used (at least to a large degree) for improving fuel economy. These policies, and steps needed to adopt and implement them successfully, are the main topic in *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a). Combinations of these policies may be needed for maximum impact and efficiency.

Three main types of policies can be used to improve fuel economy (Table 14):

- **Information and labelling:** regarding the tested and, for the consumer, expected fuel economy of any given vehicle.
- **Regulatory actions:** such as fuel economy standards or "Top Runner" type programmes (see IEA, 2012a for definitions of standard types).
- **Fiscal measures:** fuel taxes and vehicle taxes (including taxes with rebates, or "feebates"). Vehicle taxes that are differentiated based on fuel economy or CO_2 emissions are of particular interest.

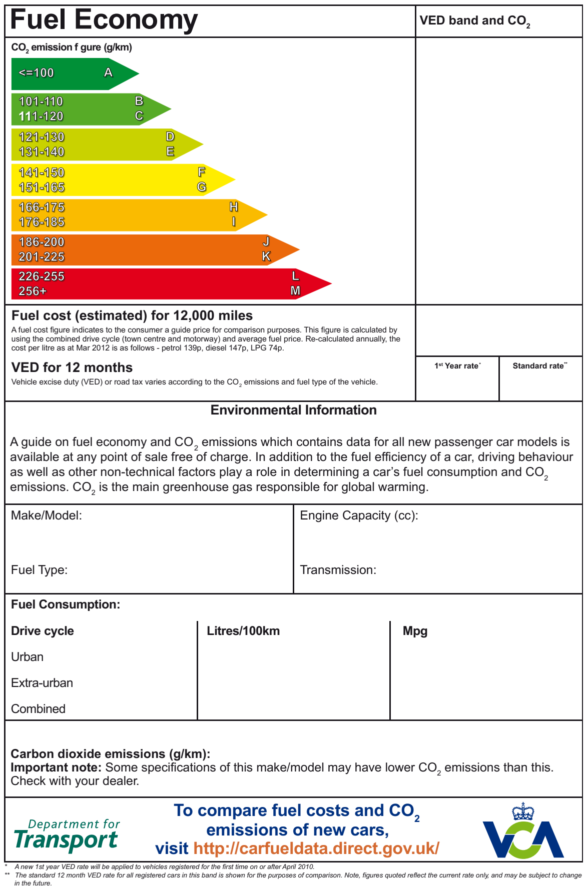
Fuel taxes and vehicle taxes/feebates are separated in Table 14 to allow a comparison between them.

Driver information/ fuel economy labelling

To encourage buyers to consider fuel economy when choosing among car models and options, they should have easy access to clear, trustworthy information about the tested and in-use fuel economy of each vehicle, and the fuel cost of using the vehicle. The most widely used form of fuel economy information is the car label displayed at dealerships. In British car dealerships, a label provides absolute data (mpg, L/100 km, gCO_2/km) and/or relative information, comparing the car with others in the same market class (Figure 17).

As alternative fuel types become more widespread – such as natural gas, electricity and biofuels – it will become more complicated to show fuel economy and CO_2 emissions on vehicle labels. Issues such as correctly reporting full "life cycle" emissions (*e.g.* upstream emissions during fuel production) become important. Cars with two fuel options (*e.g.* gasoline/biofuel flex-fuel vehicles) could have variable fuel economy or CO_2 emissions depending on the fuel mix. Careful consideration of these factors must be made in vehicle labelling. This is also true for assigning vehicle fuel economy or CO_2 scores for other policies such as standards. Rating and labelling systems provide an important basis for other policies, such as standards and fuel-economy based taxation systems, discussed further below.

Figure 17. UK car label with seven classes



Source: VCA, 2012.

Fuel economy standards

Standards for vehicles, whether voluntary or mandatory, are likely to be instrumental in steadily improving average fuel economy by encouraging or requiring manufacturers to produce more efficient vehicles. Standards push manufacturers to adopt new technologies more rapidly, while limiting or avoiding increases in vehicle size, weight and power, all of which erode the fuel savings provided by the technologies.

Standards typically require a minimum level of fuel efficiency per vehicle or as an average across a particular class of vehicles. Mandatory standards should be implemented 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.

As described in *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a), standards should be broad enough to cover all major vehicle types (at least LDVs and the full range of trucks) and should avoid "leakage" of vehicles into categories not covered by the standard. Indeed, some standards offer the possibility of having a different fuel economy target based on the vehicle size, giving an incentive to build bigger vehicles to be subject to a less stringent target. In addition, unless there are clear reasons for not doing so, standards should be based on reaching a targeted fuel efficiency performance level or CO_2 emission reduction, and not based on promoting particular technologies.

Most OECD countries and a few non-OECD countries (notably China) have introduced standards to promote LDV fuel efficiency and CO_2 reductions (Table 15). Most of these countries' have extended their standards to 2015-16, though several countries have announced intentions to extend them as far as 2025. Most standards are based on vehicle attributes, with the fuel economy target adjusted by either vehicle weight or vehicle

Table 15. Comparison of country LDV standard systems (as of August 2011)

Country or region	Target year	Standard type	Unadjusted fleet target/ measure	Structure*	Targeted fleet	Test cycle
United States/ California (enacted)	2016	Fuel economy/ GHG	34.1 mpg or 250 gCO_2/mi	Footprint-based corporate average	Cars/light trucks	US combined
United States (Supplemental Notice of Intent)	2025	Fuel economy/ GHG	49.6 mpg or 163 gCO_2/mi	Footprint-based corporate average	Cars/light trucks	US combined
Canada (enacted)	2016	GHG	153 (141) gCO_2/km	Footprint-based corporate average	Cars/light trucks	US combined
European Union (enacted)	2015	CO_2	130 gCO_2/km	Weight-based corporate average	Cars/SUVs	NEDC
European Union (proposed)	2020	CO_2	95 gCO_2/km	Weight-based corporate average	Cars/SUVs	NEDC
Australia (voluntary)	2010	CO_2	222 gCO_2/km	Fleet average	Cars/SUVs/light commercial vehicles	NEDC
Japan (enacted)	2015	Fuel economy	16.8 km/L	Weight-class based corporate average	Cars	JC08
Japan (proposed)	2020	Fuel economy	20.3 km/L	Weight-class based corporate average	Cars	JC08
China (proposed)	2015	Fuel consumption	6.9 L/100km	Weight-class based per vehicle and corporate average	Cars/SUVs	NEDC
South Korea (proposed)	2015	Fuel economy/ GHG	17 km/L or 140 gCO_2/km	Weight-based corporate average	Cars/SUVs	US combined

* For the definition of the different types of standard, please refer to IEA (2012a).

Source: adapted from ICCT, 2011b.

Box 8. Fuel economy standards for heavy-duty vehicles

Introducing fuel economy standards for HDVs is a complex task because fuel consumption of trucks depends on many factors apart from the sheer truck weight class, such as average transported payload, typical mission profiles, road gradients, drag and rolling resistance from truck as well as trailer, engine characteristics, gear ratios and type of transmission, and auxiliary power demand. If reasonable and meaningful fuel economy standards are to be achieved, all these factors need to be taken into account for each size class and truck type. To tackle these multiple factors, programmes have been developed which combine component testing and vehicle simulation, ensuring that many if not all of these variables are taken into account.

Currently, the United States and Japan have standards in place, while the European Union and China are developing them. The four are following slightly different approaches:

- The US EPA test procedure separates trucks into three categories: combination tractors, heavy-duty pick-up trucks and vocational trucks (comprising all the rest). For each class, it sets separate standards for engines and vehicles. On the vehicle side, for combination tractors only a few measures such as aero packages, low RR tyres, weight reduction, idle and speed reduction are taken into account. The impact of customer selections such as engine power and gear ratios are excluded by design. The impact of the trailer is currently not regarded but will be in the future. For vocational trucks only tyres are considered. For heavy-duty pick-ups and vans, the test procedure is an extension of the LDV test.
- The Japanese approach combines engine testing and vehicle simulation by taking into account the engine rating and torque curve profile based on an inter-urban and urban driving cycle. Before simulation, so-called fuel efficiency maps based on engine speed and torque have to be created, testing the various engines on the engine test bed. The actual test drive is then simulated, the needed engine speed and torque to propel the truck are calculated based on driving resistance (including air, acceleration and RR, based on standard values) and assumed vehicle speed (based on the underlying driving cycle). Final fuel consumption by truck type is based on a combination of urban and inter-urban driving.
- The Chinese approach is similar to the Japanese one but relies more on testing of complete vehicles on the dynamometer. The procedure envisages testing of basic vehicle types and simulation of variants. So far the definition of "basic type" and "variant" is not finalised for the various HDVs. The introduction of HDV fuel economy standards is planned for 2012.
- The approach taken by the European Union is ambitious: based on component testing (engine, air resistance, RR as well as transmission and auxiliaries) and simulation (according to test cycles with respect to mission profiles), an emission certification procedure is being developed (including the trailer). A demonstration simulation software package will be available in 2012. As the simulation tool requires a high level of detail, its development has to be well co-ordinated with the original equipment manufacturers (OEMs).

size/footprint. The advantages and disadvantages of different approaches are covered in *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a).

To date only the United States and Japan have implemented standards for freight trucks, though the European Union and China are developing these. Only China has developed standards for two- and three-wheelers.

These and many other countries could benefit considerably from further steps, including:

- ensuring standards extend well into the future, for example to 2025, as the United States is currently doing;
- ensuring standards cover all major vehicle types, including cars, trucks, buses and two-wheelers;

- ensuring standards are based on appropriate test systems and drive cycles, cover all energy-using equipment on board a vehicle, and that testing techniques minimise the difference between tested fuel economy and in-use fuel economy;
- undertaking broad programmes to improve in-use fuel economy (*e.g.* eco-driving programmes, traffic management programmes, etc.); and
- consider full upstream emissions, in order to consider not only "tank-to-wheel" (TTW) but also "well-to-tank" (WTT) GHG emissions , especially as zero tailpipe emissions vehicles gain market share.

As no country can claim to have satisfied all of these objectives, there is still great potential for policy to have a significant impact.

Fiscal measures: fuel taxes and vehicle purchase taxes/incentives

A range of fiscal measures (involving pricing and, usually, taxes or subsidies) can be used as complements to a fuel economy standard or as stand-alone policies, to influence how people buy and use cars, and to influence manufacturers' decisions about the characteristics of the cars they produce.

Fuel taxes

In theory, fuel taxes should be a perfect policy for encouraging fuel saving: every time consumers refuel, in theory, they are reminded of the cost of fuel and the benefit of saving fuel, and are thus encouraged to buy more efficient vehicles, to use them more carefully (*e.g.* eco-driving) and to reduce unnecessary travel and/or shift to more efficient modes. However, evidence suggests that consumers don't fully account for the likely lifetime fuel cost of vehicles – for example, rejecting opportunities to spend more on a fuel-efficient vehicle with a fuel savings payback period of more than two years.

Even so, fuel taxes can provide significant incremental incentives to save fuel, and are a vital part of any policy package to promote sustainable transport. But many countries currently apply low fuel taxation rates or even outright fuel subsidies, which is very counterproductive. The result is much more driving and fuel use, more traffic congestion, more emissions and greater oil imports (or less exports) with commensurate losses of foreign exchange.

Fuel taxes can provide revenues to pay for infrastructure costs and to develop sustainable transport, such as mass transit systems. They can also help cover various external costs generated by the use of road vehicles, including those due to air pollution and other health impacts, GHG emissions and other climate impacts, and losses related to traffic accidents, noise and other negative impacts. In this regard, CO_2 taxes aimed only at the compensation of GHG-related impacts would result in a relatively low charge to the retail price of motor fuels. For example, a USD 50/t CO_2 tax on gasoline would yield a EUR 0.1/L (or USD 0.45/gallon) change in price. Even higher tax levels would be needed to cover all external costs, and to significantly influence the way people buy and drive vehicles.

Vehicle taxes and incentives

Financial incentives at the point of vehicle purchase, such as vehicle taxes and rebates differentiated by fuel economy or CO_2 emissions (sometimes called "feebates" or, in French, "bonus-malus" systems), can complement standards or, in some cases, serve a similar purpose. These incentives change the effective price of a car, encouraging purchasers to choose more efficient, lower CO_2 models. By influencing the sales mix of different types of vehicles, sliding scale fee/rebate systems can not only encourage sales of the most fuel efficient vehicles in each market class, but also help avoid a drift toward larger, heavier vehicles that might occur with some kinds of fuel economy standards (such as attribute-based standards). Further, by encouraging consumers to buy the most efficient vehicles available, this policy can help the auto industry to sell their most efficient products and encourage them to introduce more fuel-efficient models.

Purchase incentive systems are generally linked to vehicle fuel economy or CO_2 rating/labelling systems, so it is necessary (as for standards) for countries to first ensure that all available vehicles are rated and that this information is easily available to consumers.

Sliding scale vehicle tax/rebate systems are often designed to be revenue-neutral, *i.e.* the total fees from vehicles that have a tax are offset by the total rebates to the purchasers of vehicles that qualify.

However, this does not have to be the case; in France during 2008-10, the Bonus-Malus system provided a net subsidy to vehicle purchases, justified in part due to the economic crisis at that time. Conversely, systems could have net tax-raising effects, such as in Denmark where the vehicle purchase tax is, on average, very high, even though the most efficient vehicles (new technology vehicles, such as electrics) receive a subsidy.

The design of vehicle tax systems linked to fuel economy or CO_2 emissions is described in *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a).

Policy combination: introducing the fuel economy readiness index

For the purposes of the *Technology Roadmap: Fuel Economy of Road Vehicles* and the *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a), the IEA has developed an index of whether a country has put in place all the elements of a relevant policy package to promote fuel economy (Table 16).

Each policy in the fuel economy readiness index has a different maximum score depending on its potential to improve fuel economy. The fuel tax scale is based on gasoline tax levels (GIZ, 2011). Other scales are based on IEA analysis. The scoring system highlights the importance of fuel taxes and fuel economy standards in improving fuel economy.

The score for a given country is the sum of the four individual scores of each policy status in the country.

Most OECD countries score five or above, showing that they have a good and improving fuel economy policy framework. Only a handful of countries do not score, mainly oil-producing countries that heavily subsidise gasoline prices. As more detailed data become available across a wide range of countries, this index and the way it is calculated will evolve to reflect trends in policy adoption and implementation.

Table 16. Fuel economy readiness index scoring system

Policy	***Score***			
	0	***1***	***2***	***3***
Fuel tax	High subsidy	Low subsidy	Low tax	High tax
Status of fuel economy standard implementation	No standard	Proposed for light vehicles	Enacted for light vehicles	Enacted or proposed for light and heavy vehicles
CO_2- or efficiency-based vehicle registration or ownership tax	No	Yes		
Availability of fuel economy labels	No	Yes		

Conclusions: key steps and timeframes for action

Improving fuel economy is a vital way to save oil and cut CO_2 emissions at a low cost to society. Fuel economy measures could cut fuel use by 30% to 50% and reduce emissions by several gigatonnes CO_2 per year across road transport modes, in the medium to longer term, in comparison with the 6DS. Some countries have had fuel economy policies for several years, but only recently have much stronger measures been adopted in major OECD markets such as the United States and the European Union, and in China. Other parts of the world, including most major emerging economies, still lack fuel economy standards or (except in a few cases) fiscal measures or even fuel economy labelling programmes.

To meet the fuel economy targets outlined in this roadmap, certain interim targets must be met, requiring key elements of policy to be put in place promptly in OECD and non-OECD countries. Although many of these have already been implemented in some countries, the challenge is to ensure they are implemented in most countries around the world, especially major economies, as soon as possible.

Countries must start the policy process very soon in order to have any influence on the vehicles sold in the 2015-20 timeframe. It is almost too late, in 2012, to set standards for 2015 – or at least standards that push very hard compared with baseline expectations. The relevant time requirements are:

- **Policy planning and development:** up to two years for full analysis, stakeholder engagement, final rulemaking.
- **Manufacturer lead time:** minimum two years from final rule to initial year of impact, to give manufacturers time to respond with changes to their product plan; three to five years will give manufacturers more flexibility and help them meet requirements at lower cost. Each succeeding year out from the data of policy adoption, a tighter target can be justified because manufacturers have more time to react (and because each year more technologies become available and/or cost-effective).
- **Time span covered by regulation:** the longer the better (ten years is a good time horizon) in order to give a clear signal for tighter standards coming in the future.

Key timeline for achieving 2DS fuel economy objectives

The IEA proposes a timeline of specific numerical targets for fuel economy of LDVs up to 2050 (Table 17). These are intended to be world average targets, excluding the effect of electric vehicles, so each country needs to develop its own targets and policies based on its national context. *Policy Pathway: Improving the Fuel Economy of Road Vehicles* (IEA, 2012a) can help to do this.

Indicative targets could also be set for trucks and two-wheelers but should be set regionally, given major differences in types of vehicles in different regions. Therefore, they are not proposed in this roadmap, apart from a general goal of a 30% to 50% reduction in truck energy use per kilometre (20% to 30% reduction for two-wheelers) in the 2030 time frame compared with 2005.

Each country should work towards the implementation of relevant policies to reach the milestones outlined in this document. Improving fuel economy of the national fleets will bring substantial benefits, such as the improvement of energy security, reduction in economic vulnerability and improvements in trade balances, through a reduced need for energy imports. Better fuel economy will help reduce CO_2 and other types of pollution, and will diminish the risk of climate change. The IEA urges all the countries to start acting now and can provide assistance, in cooperation with the Global Fuel Economy Initiative, in setting the relevant policies adapted to the local context.

Table 17. Timeline of global milestones

	2005 (base year)	*2010-15*	*2015-20*	*2020-30*	*2030-50*
Global FE target for new LDVs (Lge/100 km)	8.1	2.7% per year improvement desirable	5.4 by 2020 (34% below 2005, 2.7% annual improvement)	4.0 by 2030 (50% below 2005, 2.7% annual improvement)	Below 4 (exact target will depend on technology availability and cost, could be set by 2020)
Global FE target for entire stock of LDVs (Lge/100 km)	10.2			6.6	5.0
Fuel economy policies: OECD		Full LDV policy package in place	Full LDV policy package in place	Work toward regional alignment of policies; Push for hybridisation and electric drive technologies to help meet 2030 target	Continue push below 4 L/100 km
Fuel economy policies: Non-OECD		Labelling in major markets worldwide	Full LDV policy package in place	Work toward regional alignment of policies; Push for hybridisation and electric drive technologies to help meet 2030 target	Continue push below 4 L/100 km

Appendix I: Glossary of terms

Drive cycle: see test cycle.

EcoRoll: adding a freewheel function allows the vehicle to continue rolling with no engine braking losses without making use of the clutch.

Gap factor: difference between tested fuel economy and in-use fuel economy.

Gear shift indicator: dashboard indication of the optimal moment to shift gear on manual transmission.

Green zone indicator: indicates real-time fuel economy to encourage better driving.

Load factor: for passenger vehicles, number of people per vehicle; for freight vehicles, tonnage transported per vehicle.

Internal combustion engine (ICE): reciprocal piston engine propelled by liquid fuels; the energy released by the combustion of the fuel/air mix is converted into rotational mechanical energy through the linear motion of the piston.

Spark ignition engine: ICE in which combustion is triggered using a spark plug.

Compression ignition engine: ICE in which the air/fuel mixture is ignited using the compression and the associated rise of temperature of the mixture.

Platooning: when several vehicles are driving in a queue to reduce air friction.

Predictive cruise control: based on road topography information, the optimal speed of a vehicle is calculated taking into account slopes, which reduces unnecessary deceleration and acceleration.

Test cycle: driving pattern used for the vehicle certification.

Tested fuel economy: fuel economy of a vehicle when driving the test cycle.

In-use fuel economy: fuel economy of a vehicle in its daily usage patterns.

WTT (well-to-tank): usually refers to emissions emitted from upstream transformation processes, from the oil well to the fuel tank; it now applies to other fuel sources, such as biofuels or even electricity.

TTW (tank-to-wheel): refers to emissions released during the vehicle operation, at the vehicle tailpipe.

WTW (well-to-wheel): sum of WTT and TTW emissions.

Appendix II: Abbreviations, acronyms and units of measure

Acronyms and abbreviations

CAI	cold air induction
CO_2	carbon dioxide
ETP	*Energy Technology Perspectives*
EV	electric vehicle
FCEV	fuel cell electric vehicle
FE	fuel economy
GDI	gasoline direct injection
GFEI	Global Fuel Economy Initiative
GHG	greenhouse gas
HDV	heavy-duty vehicles
ICE	internal combustion engine
IEA	International Energy Agency
ITF	International Transport Forum
LED	light-emitting diode
MAC	mobile air conditioning
NGOs	non-government organisations
NEDC	New European Driving Cycle
OECD	Organisation for Economic Co-operation and Development
PHEVs	plug-in hybrid electric vehicles
PTWs	powered two-wheelers
RR	rolling resistance
SPT	Directorate of Sustainable Energy Policy and Technology
SUV	sport utility vehicle
TTW	tank-to-wheel (see glossary of terms)
VVA	variable valve actuation
VVTL	variable valve timing and Lift
WTT	well-to-tank (see glossary of terms)
WTW	well-to-wheel (see glossary of terms)

Units of measure

EJ	exajoules
$GtCO_2$	gigatonnes of CO_2
gCO_2/km	grammes CO_2 per km
L/100 km	litres per 100 km
Lge/100 km	litres gasoline equivalent per 100 km
mpg	miles per gallon
tCO_2	tonnes of CO_2
t	tonnes

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Technology Roadmap Fuel Economy of Road Vehicles

International Energy Agency – IEA
9 rue de la Fédération, 75015 Paris, France
Tel: +33 (0)1 40 57 65 00/01, Fax: +33 (0)1 40 57 65 59
Email: info@iea.org, Web: www.iea.org