



EU Transport GHG: Routes to 2050?

Technical GHG reduction options for fossil fuel based road transport

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11 February 2010

Partners



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Executive Summary

Vehicles powered by internal combustion engines (ICEs) running on fossil fuels are expected to remain the dominant technology in market for road transport vehicles in the decades to come. Even for the period 2030 - 2050 a significant market share is to be expected. Improvements in fuel efficiency of ICE-powered vehicles (ICEVs) will therefore continue to have a significant impact on absolute GHG emissions from road transport, even though their relative importance may be expected to decrease over time. In the longer term it is as yet difficult to predict which technologies will take over the dominant position of the ICE. Generally, however, many principles that are valid for improving the overall efficiency of ICEVs are also applicable to vehicles with alternative propulsion systems and energy carriers.

This paper focuses on technological options for improving fuel efficiency of ICE-powered road vehicles (passenger cars, light commercial vehicles, trucks and buses). Options such as vehicle down-sizing and performance downrating, which obviously lead to lower fuel consumption and CO₂ emissions, are outside the scope of this paper. The associated acceptance aspects and welfare effects make such measures behavioural options rather than technological options.

Principles

In improving the efficiency of an ICE-powered vehicle there are several 'strategies' that can be followed, separately or combined:

- Improvement of the combustion process
- Decrease of mechanical losses in the engine (friction and pumping losses)
- Decrease of mechanical losses in the transmission¹
- Decrease of inertial 'losses' (i.e. energy irreversibly expended to accelerate the vehicle's mass) and losses due to aerodynamic drag and rolling resistance
- Recuperation of energy (e.g. kinetic energy upon braking or waste heat from the exhaust)
- Reduction of energy demand from peripheral processes (i.e. by improving the efficiency of auxiliary components)

Also important to note is that the average efficiency of an engine is strongly related to the way it is used. Driving style, traffic situations (e.g. speed limits and congestion), and the ratio of urban, rural and highway driving all influence a vehicle's energy consumption and the average efficiency of the engine. To ensure that the technological efforts spent on improving energy efficiency on the standardized test used for type approval lead to similar improvements in real world GHG emissions, it is important to measure fuel efficiency in such a way that it is closely related to fuel efficiency in real world driving.

Engine and powertrain improvements for internal combustion engines

Options on the engine typically relate to improvements of the combustion process and engine downsizing in order to reduce friction losses. Options that are foreseen to be applied in light duty vehicles in the short- to mid-term future are [33]:

- Reduced engine friction losses (~3% reduction potential)
- Variable valve timing (~3% reduction potential)
- Variable valve control (~7% reduction potential)
- Variable compression ratio's (~10% reduction potential)
- Direct injection (homogeneous charge, stratified charge) (~3% - 10% reduction potential)
- Downsizing with turbocharging (~10% - 20% reduction potential)
- Cylinder deactivation (~8% - 25% reduction potential)

¹ i.e. mechanical losses in the train of energy transfer from the engine to the wheels.

- Homogeneous charge compression ignition/controlled auto-ignition (diesel like GHG emissions for petrol vehicles)
- A change in fuel type (reduction potential dependant on the combustion improvements).

The transmission is a system that matches the required power at the wheels for any velocity of the vehicle with the engine's available rotational velocity and torque. From a CO₂ emissions point of view a good transmission should always force the engine to run in the most efficient operating point that matches its desired power output. Options that are foreseen for the short to mid-term future are:

- Optimized gearboxes (~2% reduction)
- Dual-clutch gear boxes (~5% - 15% reduction)

By combining the internal combustion engine with one or more electric machines and a storage device for electrical energy (generally a battery) various hybrid powertrain configurations can be realised. Compared to advanced gear boxes, hybrid power trains offer further possibilities for optimising the engine operation with respect to efficiency. Efficiency improvements of some 10 – 25%, depending on powertrain configuration and level of hybridisation, are realised by decoupling of engine speed from vehicle speed, leading to optimised choice of engine operating points (Section 2.2.1) and reduced transient behaviour, by the possibility of pure electric driving in situations where the engine would operate inefficiently in part load, the avoidance of peak loads on the engine by providing peak power from the electric motor, and by recuperation of braking energy.

To a more limited extent, recuperation of braking energy can also be applied to vehicles with a conventional engine.

In the coming years heat recovery from the exhaust or the engine's cooling system is also expected to become an important option for optimising energy efficiency of ICEVs. Using e.g. a Rankine Cycle, mechanical or electrical turbo-compounding, or a thermo-electrical generator waste heat can be converted into mechanical or (in most applications) electrical power, which can e.g. be used to power auxiliaries. In a hybrid powertrain it can also be stored for later use in propulsion.

Reducing the energy needed for propulsion and auxiliaries

Important routes to reducing the energy needed for propulsion and auxiliaries are:

- Weight reduction (up to 20% CO₂ emissions reduction)
- Improvement of the aerodynamic properties (~5% reduction)
- Reduction of friction losses (~3% reduction)
- Waste heat recovery (~5%-30% reduction)
- Improvement of the energy efficiency of components (dependent on the components)

Considerations for heavy goods vehicles

Important aspects of heavy goods transport are:

- Road vehicles for heavy goods transport are already designed to minimise operational costs. This means that energy efficiency has achieved more attention in this segment than in light duty vehicles.
- The large range of vehicle configurations used for different freight transport applications implies that fuel saving options should be tailored to the specific transport application and its demands.

Technological options for fuel saving in heavy goods transport are generally similar to the options described above for light duty ICE vehicles with some specific caveats.

Uptake of fuel saving technology in HD vehicles is already strongly market driven. Peculiarities of the HGV industry, however, sometimes impede this uptake. Such peculiarities are:

- A long lifetime of a trailer, which implies a long penetration time for new technology
- Relatively high R&D costs because of challenging requirements and limited technology cross-over from the cars market
- Low truck market volumes
- Trailer owners, typically, do not benefit from fuel savings
- Very small margins in the trucking industry

Assessment of measures

The efficiency of measures should be related to trends in the reference situation. Current trends that affect overall CO₂ emissions are:

- The continuing increase in performance as well as weight of passenger cars
- Vehicle legislation relating to safety and pollutant emissions leading to increased weight and energy consumption
- Increasing overall transport volumes leading to more vehicle kilometres driven.

Furthermore it should be noted that more stringent type approval requirements for pollutant emissions may for some time and to some extent limit improvements in fuel efficiency.

A cost efficient way of reducing GHG emissions is by training drivers to apply a fuel efficient driving style. In the long term, however, technological options will dampen the effect of vehicle dynamics at the level of the engine to such an extent that a driver will have only a marginal opportunity to influence fuel consumption.

Generally, the more GHG reduction is required, the more expensive the options are. The options discussed in this paper may be expected to achieve full penetration by 2030, which means that by 2050 they may have benefited heavily from learning effects. From marginal abatement cost curves it can be learned that improvements on the conventional drive train are generally compensated but also that their overall reduction potential is relatively small.

Co-benefits of employing GHG reducing options are mainly restricted to an increase in security of energy supply and the economic effects of technology spill over from the automotive sector into other markets.

On the consumer market the barriers for adopting GHG reducing technology are mainly the (perceived) consumer preferences, which now tend towards more performance and luxury rather than towards fuel economy. This is also related to the difficulty that consumers have in appreciating the long term fuel saving benefits in relation to the short term purchase cost increase associated with applying CO₂ emission reducing technologies (consumer myopia). On the HGV market costs are perceived more rationally, and the barriers are mostly related to the way this industry operates (i.e. transport requirements and operational issues such as ownership).

Conclusions

The internal combustion engine determines the benchmark of what consumers expect from their vehicles in terms of behaviour, reliability and costs. Vehicles equipped with ICEs may be expected to continue to have a significant share among the propulsion systems for the various modes of road transport in the future. ICEs still have significant potential for efficiency improvement on a per vehicle basis and, therefore, the technological options to decrease GHG emissions from fossil fuel based road transport can have a significant effect on the overall reduction by 2050.

Many options can be implemented in the short to medium term. Technical options to reach demanding CO₂ reduction targets on the vehicle level will always be expensive in first instance. Full penetration of the technological options may be expected by 2030, however, and therefore by 2050 significant cost reduction because of learning effects may be expected. Options, such as

fuel efficient driving will become less effective as technological options will increasingly dampen the effects of driving dynamics on engine efficiency.

Hybridization is an expensive option compared to downsizing, which represents a similar reduction potential but which can be achieved at lower cost. Hybridization, however, should also be viewed in the light of enabling energy saving options that rely on the availability of sufficient electrical power. At the same time the availability of more on-board electric energy may also lead to application of additional energy consuming features.

Weight reduction may significantly contribute to fuel efficiency improvement if the weight advantage is not used to increase vehicle performance or to enable added safety features. Safety measures in general will lead to an increase in mass and fuel consumption. This may be countered by including safety not in the vehicle design but in the vehicle intelligence. Friction losses from rolling resistance or sub-optimal lubricants contribute a few percent to the fuel consumption. LRRTs, TPMS and low viscosity lubricants can therefore increase the reduction potential by an equal few percent. A few percent can also be gained by recuperating waste heat energy. A few percent of reduction potential can furthermore be gained from improving the energy efficiency of components. Specifically noteworthy are mobile air conditioners (MACs) that do not only contribute to the GHG emissions by way of their energy consumption but also because of possible leakage of their refrigerant, which currently is a type that has a high GWP². In the near future, however, it is mandated that MACs will be operated with low GWP refrigerants.

The CO₂ reduction potential of heavy duty vehicles is relatively small because they are already relatively efficient. Also, because of the typical lifetime of trailers, the options on the trailer design (such as lightweight construction and aerodynamic design) will have a long penetration time. A more explicit split in vehicle technology for urban and highway vehicles may become apparent in the future. Changes in legislation may increase the span of fuel efficiency improvement options, for example by increasing the maximum load or length of heavy duty vehicles or by diversification of the safety requirements for urban and highway transport.

² Global Warming Potential: the effect of 1 gram of HFC-134a (the currently most used refrigerant) on global warming is equivalent to that of 1300 gram of CO₂.

1 Introduction

1.1 Topic of this paper

This paper is one of five papers on GHG reduction options for transport drafted under the *EU Transport GHG: Routes to 2050?* project. These papers review the options – technical and non-technical – that could contribute to reducing transport’s GHG emissions, both up to 2020 and in the period from 2020 to 2050. All papers aim to provide a high-level summary of the evidence based on existing studies.

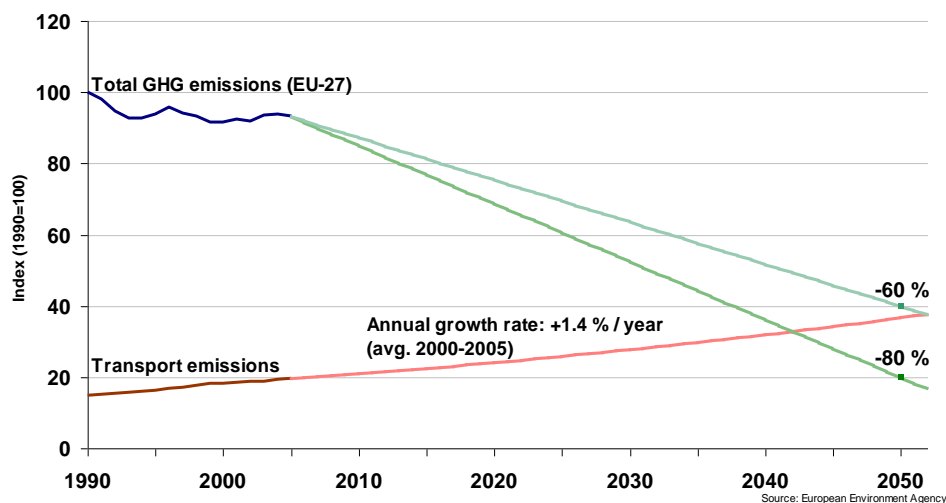
This paper focuses on the technological options that are foreseen to reduce the CO₂ emissions from fossil fuel based road transport. It will review options that improve the power train efficiency, options that reduce the required energy for propulsion and options that improve the energy efficiency of those vehicle components that are not part of the propulsion system.

This paper was presented in draft form to a Technical Focus Group meeting (at which stakeholders were present) in July 2009 after which it has been updated on the basis of the discussion at the meeting and the comments and further evidence that were received.

1.2 The contribution of transport to GHG emissions

The EU-27’s greenhouse gas (GHG) emissions from transport have been increasing and are projected to continue to do so. The rate of growth of transport’s GHG emissions has the potential to undermine the EU’s efforts to meet potential, long-term GHG emission reduction targets if no action is taken to reduce these emissions. This is illustrated in Figure 1 (provided by the EEA), which shows the potential reductions that would be required by the EU if economy-wide emission reductions targets for 2050 of either 60% or 80% (compared to 1990 levels) were agreed and if GHG emissions from transport continued to increase at their recent rate of growth. The figure is simplistic in that it assumes linear reductions and increases. However it shows that unless action is taken, by 2050 transport GHG emissions alone would exceed an 80% reduction target for all sectors or make up the vast majority of a 60% reduction target. This illustrates the scale of the challenge facing the transport sector given that it is unlikely that GHG emissions from other sectors will be eliminated entirely.

Figure 1: EU overall emissions trajectories against transport emissions (indexed)³

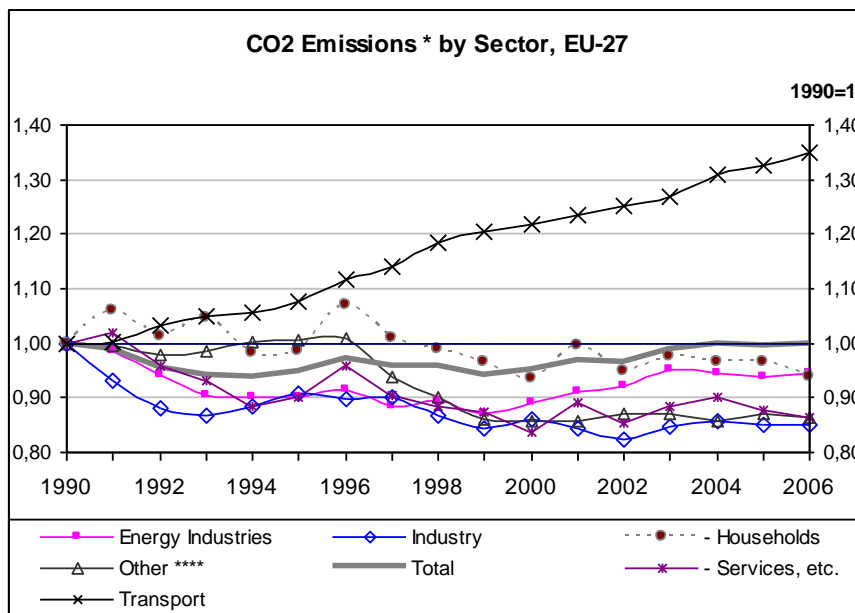


The extent of the recent growth in transport emissions is reinforced by Figure 2, which presents a sectoral split of trends in CO₂ emissions over recent years. Whilst the CO₂ emissions from other

³ Graph supplied by Peder Jensen, EEA

sectors have levelled out or have begun to decrease, transport's CO₂ emissions have risen steadily since 1990. It should be noted that whilst Figure 2 is presented in terms of CO₂ emissions, very similar trends are evident for GHG emissions (in terms of CO₂ equivalent) since CO₂ emissions represent 98% of transport's GHG emissions.

Figure 2: Carbon dioxide emissions by sector EU-27 (indexed)⁴



Notes:

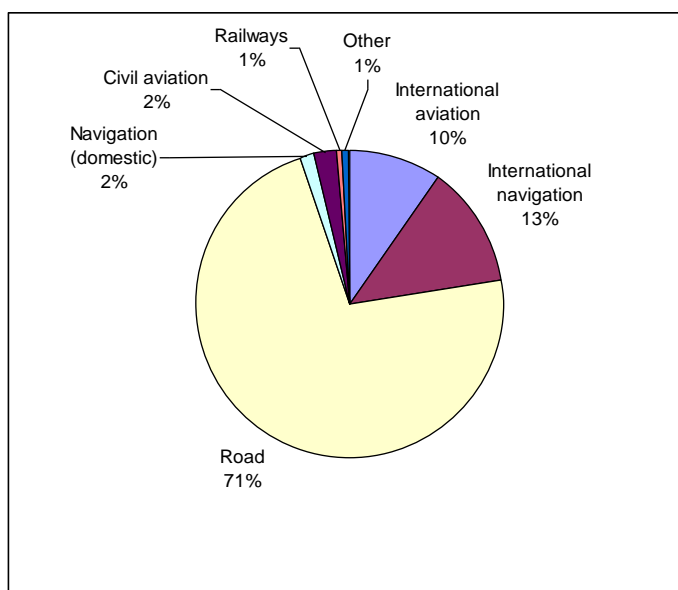
- i) The figures include international bunker fuels (where relevant), but exclude land use, land use change and forestry
- ii) The figures for transport include bunker fuels (international traffic departing from the EU), pipeline activities and ground activities in airports and ports
- iii) "Other" emissions include solvent use, fugitive emissions, waste and agriculture

The vast majority of European transport's GHG emissions are produced by road transport, as illustrated in Figure 3, while international shipping and international aviation are other significant contributors.

Recent trends in CO₂ emissions from transport are also expected to continue, as can be seen from Table 1 below. Between 2000 and 2050, the JRC (2008) estimates that GHG emissions from domestic transport in the EU-27 will increase by 24%, during which time emissions from road transport are projected to increase by 19% and those from domestic aviation by 45%. It is important to note that these projections do not include emissions from international aviation and maritime transport, which are also expected to increase due to the growth in world trade and tourism.

⁴ Graph based on figures in DG TREN (2008) *EU energy and transport in figures 2007-2008: Statistical Pocketbook* Luxembourg, Office for Official Publications of the European Communities.

Figure 3: Greenhouse gases emissions by transport mode (EU-27; 2005)⁵



Note: The figures include international bunker fuels for aviation and navigation (domestic and international)

Table 1: CO₂ emissions projection for 2050 by end-users in the EU-27, in Millions tonnes of CO₂⁶

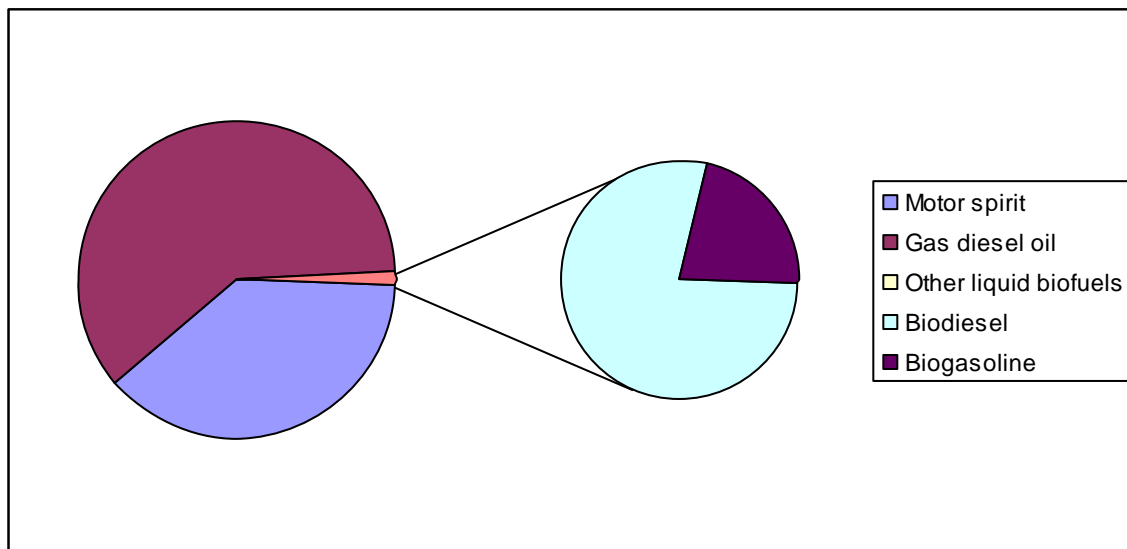
End user Category	1990	2000	2010	2020	2030	2050
Road transport	695	825	905	980	1002	1018
Rail	29	29	27	27	21	20
Domestic Aviation	86	134	179	206	237	244
Inland navigation	21	16	16	17	17	17
Total	810	988	1110	1213	1260	1299

Figures from the EEA (2008), illustrate the recent growth in GHG emissions from international aviation, as they estimate that these increased in the EU by 90% (60 Mt CO₂ equivalent) between 1990 and 2005; international aviation emissions will thus become an ever more significant contributor to transport's GHG emissions if current trends continue. Furthermore, the IPCC has estimated that the total impact of aviation on climate change is currently at least twice as high as that from CO₂ emissions alone, notably due to aircrafts' emissions of nitrogen oxides (NO_x) and water vapour in their condensation trails. However, it should be noted that there is significant scientific uncertainty with regard to these estimates, and research is ongoing in this area.

⁵ Graph based on figures in EEA (2008) *Climate for a transport change – TERM 2007: Indicators tracking transport and environment in the European Union* EEA Report 1/2008, Luxembourg, Office for Official Publications of the European Communities.

⁶ Taken from JRC (2008) *Backcasting approach for sustainable mobility* Luxembourg, EUR 23387/ISSN 1018-5593, Office for Official Publications of the European Communities.

Figure 4: Final transport energy consumption by liquid fuels in EU-27 (2005), ktoe⁷



The principal source of transport's GHG emissions is the combustion of fossil fuels. Currently, petrol (motor spirit), which is mainly used in road transport (e.g. in passenger cars and some light commercial vehicles in some countries), and diesel, which is used by other modes (e.g. most vans, heavy duty road vehicles, some railways, inland waterways and maritime vessels) in various forms, are the most common fuels in the transport sector (see Figure 4). Additionally, liquid petroleum gas (LPG) supplies around 2% of the fuels for the European passenger car fuel market (AEGPL, 2009⁸), while the main source of energy for railways in Europe is electricity, neither of which are included in Figure 4. While, alternative fuels are anticipated to play a larger role in providing the transport sector's energy in the future, currently they only contribute 1.1% of the sector's liquid fuel use.

1.3 Background to project and its objectives

The context of the *EU Transport GHG: Routes to 2050* is the Commission's long-term objective for tackling climate change, which entails limiting global warming to 2°C and includes the definition of a strategic target for 2050. The Commission's President Barroso recently underlined the importance of the transport sector in this respect by noting that the next Commission "needs to maintain the momentum towards a low carbon economy, and in particular towards decarbonising our electricity supply and the transport sector"⁹. There are various recent policy measures that are aimed at controlling emissions from the transport sector, but these measures are not part of a broad strategy or overarching goal. Hence, the key objective of this project is to provide guidance and evidence on the broader policy framework for controlling GHG emissions from the transport sector. Hence, the project's objectives are defined as to:

- Begin to consider the long-term transport policy framework in context of need to reduce greenhouse gas (GHG) emissions economy-wide.
- Deal with medium- to longer-term (post 2020; to 2050), i.e. moving beyond recent focus on short-term policy measures.
- Identify what we know about reducing transport's GHG emissions; and what we do not.
- Identify by when we need to take action and what this action should be.

⁷ Graph based on figures in DG TREN (2008), page 206

⁸ European LPG Association (2009) *Autogas in Europe, The Sustainable Alternative: An LPG Industry Roadmap*, AEGPL, Brussels. See <http://www.aegpl.eu/content/default.asp?PageID=78&DocID=994>

⁹ http://ec.europa.eu/commission_barroso/president/pdf/press_20090903_EN.pdf

Given the timescales being considered, the project will take a qualitative and, where possible, a quantitative approach. The project has three Parts, as follows:

- Part I ('Review of the available information') has collated the relevant evidence for options to reduce transport's GHG emissions, which was presented in a series of Papers (1 to 5), and is in the process of developing four policy papers (Papers 6 to 9) that outline the evidence for these instruments to stimulate the application and up take of the options.
- Part II ('In depth assessment and creation of framework for policy making') involves bringing the work of Part I together to develop a long-term policy framework for reducing transport's GHG emissions.
- Part III ('Ongoing tasks') covers the stakeholder engagement and the development of additional papers on subjects not covered elsewhere in the project.

As noted under Part III, stakeholder engagement is an important element of the project. The following meetings were held:

- A large stakeholder meeting was held in March 2009 at which the project was introduced to stakeholders.
- A series of stakeholder meetings (or Technical Focus Groups) on the technical and non-technical options for reducing transport's GHG emissions. These were held in July 2009.
- A series of Technical Focus Groups on the policy instruments that could be used to stimulate the application of the options for reducing transport's GHG emissions. These were held in September/October 2009.
- Two additional large stakeholder meetings at which the findings of the project were discussed.

As part of the project a number of papers have been produced, all of which can be found on the project's website, as can all of the presentations from the project's meetings.

1.4 Background and purpose of the paper

This paper is one of five "options" papers (Papers 1 to 5) that were developed under the *EU Transport GHG: Routes to 2050* project. The aim of these papers was to review the technical and non-technical options that could contribute to reducing transport's GHG emissions, both up to 2020 and in the period from 2020 to 2050. A series of papers (Papers 1 to 6) on "policy instruments" that could be used to stimulate the application and take up of these options was also developed. For the purpose of the project, we used the following definitions:

- **Options** deliver GHG emissions reductions in transport – these can be technical, operational or modal shift.
- **Policy instruments** may be implemented to promote the application of these options.

The options were reviewed in the following papers:

1. Technical options for fossil fuel based road transport
2. Alternative energy carriers and powertrains
3. Technical options for non-road transport modes
4. Operational options for all modes
5. Modal split and decoupling

This paper is the first in this series of papers, all of which use evidence from existing studies to assess each of the options. It was presented in draft form to a Technical Focus Group meeting (at which stakeholders were present) in July 2009 after which it has been updated on the basis of the discussion at the meeting and any comments and further evidence received. This revised version of the paper is also available from the projects' website.¹⁰

¹⁰ <http://www.eurtransportghq2050.eu>

1.5 Structure of the paper

This paper aims to present an overview of evidence from existing studies relating to the CO₂ emission reduction potential of technical options in fossil fuel based road transport. This means that this paper will focus on reducing the GHG emissions by:

1. Increasing the efficiency of converting fuel energy to work
 - a. Giving an overview of the principles underlying improvements in the power train efficiency (Chapter 2) and
 - b. (Non-exhaustively) discussing some of the advanced options that can presently be foreseen (Chapter 3); and by
2. Reducing the required work for operating a vehicle (Chapter 4) by
 - a. Reducing the energy losses associated with the actual propulsion of a vehicle; and
 - b. Reducing the energy consumption by auxiliary systems.

Because fuel consumption ties heavily in with the economic model for professional heavy goods transport there is a chapter dedicated to some issues that might influence the use of the technological options that are discussed in this paper (Chapter 5).

In a final chapter the options will be broadly assessed in terms of their overall reduction potential, the timeframe and potential of their application and the costs that are involved with this (Chapter 6).

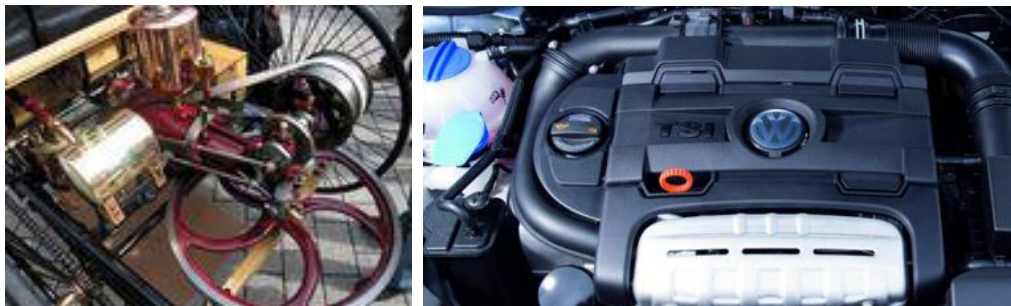
The paper does not focus on the possibilities offered by a change to less carbon-intensive fuels or alternative power trains (electric vehicles, plug-in hybrids, fuel cells, etc.), which will be addressed in Paper 2. The paper focuses on all modes of motorised road transport. It does not discuss other transport options, such as inland shipping or rail transport. Technical options for these other modes are addressed in Paper 3.

2 General considerations

2.1 The case for improving vehicles running on fossil fuels

Currently, the internal combustion engine (ICE) is by far the most common mode for propulsion in road transport and has been so ever since mechanical vehicles replaced the horse and carriage as the dominant form of road transport. This means that ICEs can benefit from more than a hundred years of engineering experience and (efficiency) optimisation (Figure 5). Furthermore, there is a vast infrastructure in place to support this industry.

Figure 5: Ages apart in time and performance: Left panel, a picture of the ICE on a replica of the 1886 'Benz patent-motorwagen nummer 1', capable of 0.9 bhp[1, 2]; right panel, a picture of a Volkswagen 1.4 Litre TSI Twincharger engine, the 'Engine of the Year 2009', capable of 178 bhp[3, 4].



Any alternative propulsion system needs to compete with this, not only in terms of costs but also in terms of consumer acceptance¹¹ and its actual efficiency¹². For these reasons, it is expected that ICE technology will remain competitive for the foreseeable future with even in 2050 a significant share on the transport market. Consequently, it may be expected that (especially in view of an increasing transport demand) the use of carbon-based fuels will continue to have a large share. This is reflected in estimates by the World Business Council for Sustainable Development (WBCSD), which show a continued increase of the carbon-based fuels up to the year 2050 (Figure 6). Improvements on the efficiency of ICE vehicles, therefore, will continue to have a great reduction potential in absolute terms¹³. The potential to improve the fuel efficiency of conventional vehicles, however, is limited by physics. Moreover, the costs to further reduce CO₂ emissions will be relatively high in the future given that combustion engine technology is already highly developed, especially in Europe, where most progress has been made on fuel efficiency so far¹⁴.

Historically, although efficiency of transport has increased, the gains in efficiency have not been entirely devoted to reducing overall fuel consumption [16]. Whether or not there is a self-contained market case (i.e. not dependent on external stimuli such as government support) for efficiency improvements depends very much on the oil price. Higher oil prices lead to an acceptable payback period for the innovations but it should be borne in mind that consumers tend to rate the short term investment costs higher than the long term benefits of improved fuel economy ('consumer myopia'). Since costs and savings-benefits are somewhat balanced for current fuel prices, cost efficiency of reduction options is extremely important. Future relative cost development of fossil fuels is very uncertain.

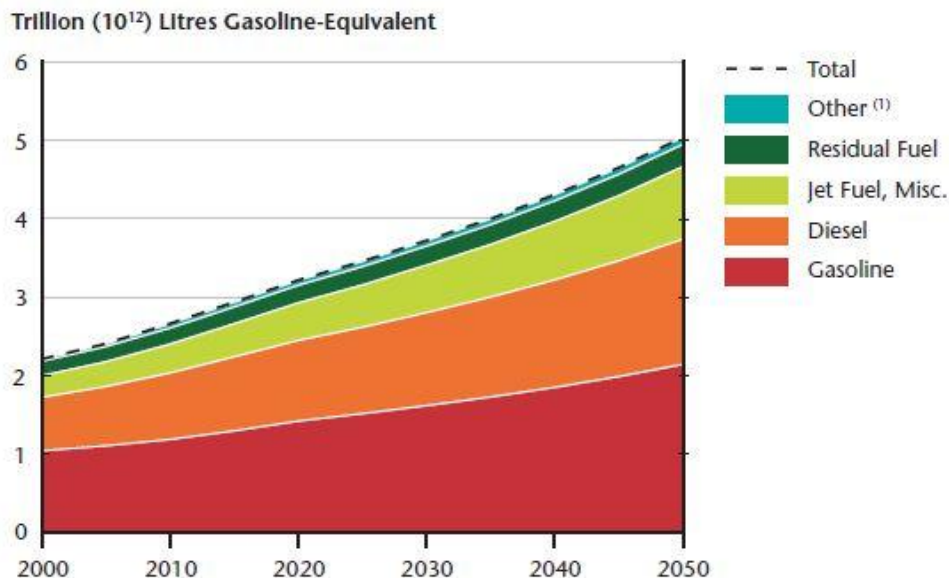
¹¹ Consumers are used to the characteristics of ICE vehicles but may feel limited by the different characteristics of e.g. electrical vehicles.

¹² Since innovative technologies have not the benefit of years of optimisation, they will initially be some way from their theoretical optimal efficiency.

¹³ It should be noted, of course, that technological options might not be the most cost-efficient means of reducing GHG emissions from transport but other options are discussed in the other papers.

¹⁴ From: 'ACEA Comments On Transport GHG Routes 2050'

Figure 6: With a projected increased volume of transport activity (Task 2) and a relatively unchanged modal mix of transportation activity, petroleum-based fuels -- gasoline, diesel fuel, and jet fuel -- are still projected to dominate transportation in 2050. Figure reproduced from [39] ('Other ⁽¹⁾' denotes CNG\LPG, Ethanol, Biodiesel, and Hydrogen).



2.2 Principles

In improving the efficiency of an ICE-powered vehicle there are several 'strategies' that can be followed either each in isolation or combined:

- Improvement of the combustion process
- Decrease of mechanical losses in the engine (friction and pumping losses)
- Decrease of mechanical losses in the transmission¹⁵
- Decrease of inertial 'losses' (i.e. energy irreversibly expended to accelerate the vehicle's mass) and losses due to aerodynamic drag and rolling resistance
- Recuperation of energy (e.g. kinetic energy upon braking or waste heat from the exhaust)
- Reduction of energy demand from peripheral processes (i.e. by improving the efficiency of auxiliary components)

Most of these options that are currently foreseen for the short, to mid-term future have recently been reviewed extensively [33].

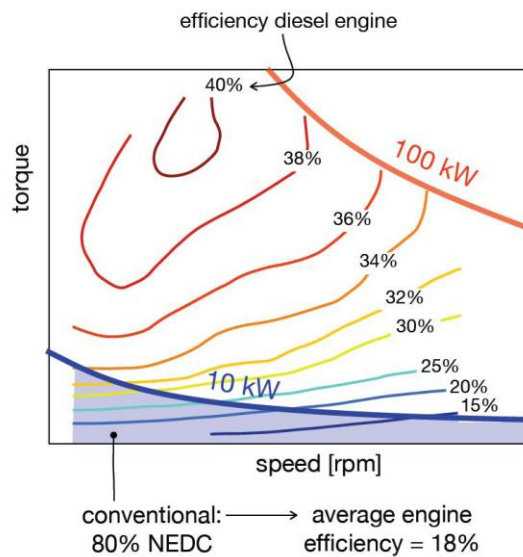
2.2.1 Engine map

It is important to note that the fuel efficiency of an ICE, and therefore its GHG emissions, depends on the load that is applied to it and this may be expressed as the product of the engine's rotational velocity and torque. Typically, an ICE is more efficient at higher loads (Figure 7).

Most engines can provide far more power than is required for by far the largest part of their use. One way of improving a vehicle's efficiency thus is to use a smaller engine, which will operate for a larger part of its usage close to full load. This will, of course, be at the expense of available power and will therefore reduce (perceived) added value to the consumer.

¹⁵ I.e. mechanical losses in the train of energy transfer from the engine to the wheels.

Figure 7: Graphical representation of an engine map for a diesel with a rated power of 100 kW. On the NEDC (Section 2.2.2) such engine will run for 80% of the cycle at an average efficiency of 18%. Image reproduced from [21].



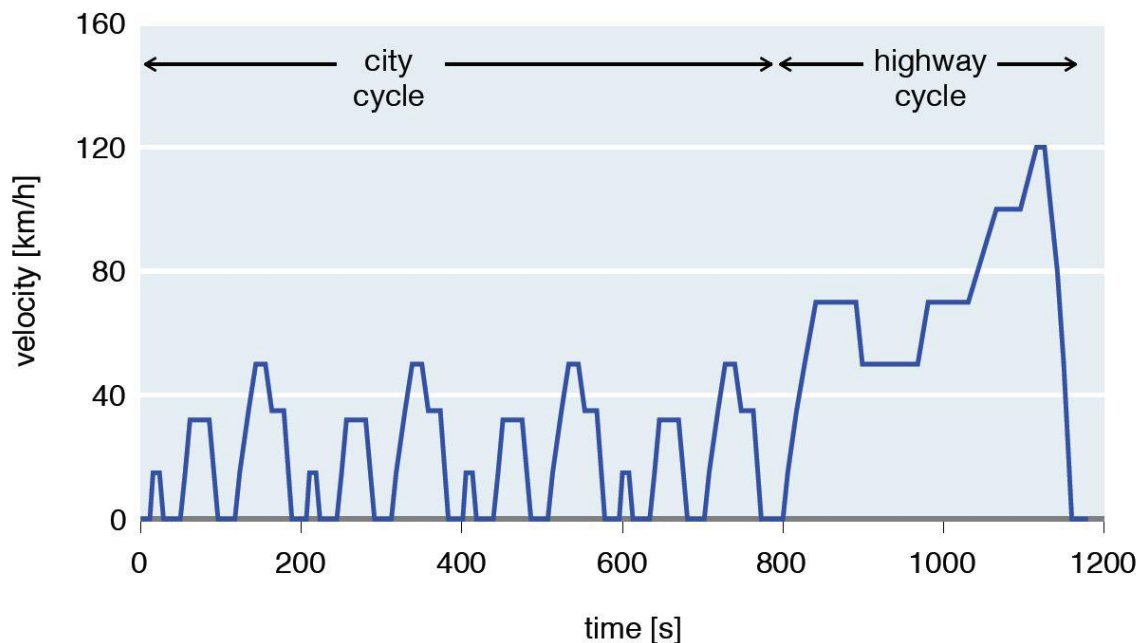
Another way to allow use of an engine's maximum efficiency is to either run a smaller engine continuously, or a full size engine intermittently, at full power and buffering the excess energy. This would typically require an additional power source in the drivetrain to convert this excess energy back into propulsion and implies therefore hybridisation. The ability of buffering excess energy also introduces the possibility of recuperating braking losses. These are major reasons why charge-sustaining hybrids are more efficient than pure ICEs even though in both cases all the energy that is required for propulsion eventually is supplied by in-car combustion of fossil fuel. Particularly the ability in hybrids to reuse braking energy allows the fuel efficiency to increase above the maximum engine efficiency (which is about 30%-40%).

2.2.2 The New European Driving Cycle

As mentioned above, fuel efficiency is strongly related to the way an engine is used because an ICE's efficiency depends on the load that is applied to it. For this reason it e.g. matters if the same vehicle is mainly used to commute within a city or to travel longer distances on a highway. To assess, in a well defined and standardised way, a vehicle's performance with respect to relevant driving circumstances, use is made of so-called driving cycles.

A driving cycle is a driving pattern, expressed in a series of velocities as a function of time, which is designed to represent a vehicle's usage (Figure 8). Evaluation of the vehicle's environmental performance takes place by measuring a vehicle's emissions on a chassis dynamometer, on which the vehicle is made to follow the cycle's driving pattern. Importantly, a vehicle's fuel economy is only determined with respect to a certain driving cycle. How well this correlates with the actual emissions of such vehicle depends on how well the driving cycle correlates to real world driving. In Europe, the so-called New European Driving Cycle (NEDC, Figure 8) is the official driving cycle used for vehicle type approval. This is, therefore, in Europe currently the most important pattern against which fuel efficiency (and thus GHG emission) from ICEVs is evaluated. Crucially, there is some discrepancy (typically 10% - 20%) between the fuel consumption as measured on the NEDC and that in real world driving. Currently a new cycle is, therefore, being developed that aims at a better correlation.

Figure 8: Graphical representation of the New European Driving Cycle, which is the regulated European cycle for defining the specific fuel consumption (in litres per 100 km) and pollutant emissions of passenger cars.



Since evaluation of the vehicle's performance takes place by measuring its emissions on a chassis dynamometer, the effect of some applications that are not in use during these tests, such as power steering or options that the driver can switch off, do not show. If there is no self-contained market case for improving fuel economy, measures should be taken so that there will be incentives for also improving the efficiency of these options.

2.3 Eco-driving

By slightly changing their driving style, car users can significantly reduce fuel consumption and CO₂ emissions. This is, of course, not a technical option but as its impact is partly based on the technical characteristics of the internal combustion engine it will be briefly discussed here. Applying "eco-driving" is done by following these instructions:

- shift into a higher gear early, maintain a steady speed in the highest possible gear, anticipate traffic flow and switch off the engine at short stops;
- check and adjust the tyre pressure regularly;
- make use of in-car fuel saving devices such as on-board computers and dynamic navigators;
- remove surplus weight and unused roof racks.

Training programmes have been developed to meet new requirements for professional driver competence. All commercial vehicle drivers will be required to undertake this training on a five-year basis. But manufacturers have offered courses that encourage more eco-friendly, safe driving since the 1960s. Skills learned by operators are helping to boost fuel efficiency by around 10% and contribute to the safety of drivers and all road users. Some of the key skills taught to professional drivers include:

- adopting a driving style that anticipates hazards ahead for quicker reactions;
- selecting the right gear to stay in the engine's most economic speed regime;
- using cruise control for smooth driving;
- block shifting gears when safe to do so;

- recognising tyre maintenance, pressure, condition and axle alignment as key safety and economy issues.

In individual cases, e.g. depending on the initial driving style of the driver, and directly after receiving training the fuel economy benefits of eco-driving may be as high as 20-25%. On average, however, eco-driving training leads to fuel economy improvements with a significant long-term effect of 5-10% under everyday driving conditions. Eco-driving can be made part of the training course for new drivers, as is already the case in several countries. The European Climate Change Programme calculated that the CO₂ reduction potential of eco-driving would be in the order of 50 million tonnes of CO₂ emissions in Europe by 2010. Research clearly indicates that eco-driving is highly cost-effective with estimated cost savings of up to € 128 per tonne CO₂ saved¹⁶.

¹⁶ From: ACEA comments on 'Transport GHG Routes 2050'

3 Engine and power train improvements for internal combustion engines

3.1 Options on the engine

Options on the engine typically relate to improvements of the combustion process and engine downsizing in order to reduce friction losses. Options that are foreseen for the short- to mid-term future are [33]:

- Reduced engine friction losses
- Variable valve timing
- Variable valve control
- Variable compression ratio's
- Direct injection (homogeneous charge, stratified charge)¹⁷
- Downsizing with turbocharging
- Cylinder deactivation
- Homogeneous charge compression ignition/controlled autoignition¹⁸

3.1.1 Reduced engine friction losses

Reduction of engine friction can be achieved by the application of low friction designs, low friction materials and lubricants. Examples are¹⁹:

- the reduction of the angle of the rod that connects the piston to the crankshaft at the moment of combustion;
- the application of low-friction coatings;
- the application of low-tension rings; or
- the use of reduced diameter bearings.

The short-to-medium term reduction potential may be estimated at approximately 3%.

3.1.2 Variable valve timing

Valves control the air and fuel intake and exhaust expulsion of the engine's combustion chambers (cylinders). During each cycle these valves are opened and closed for a certain amount of time. This amount of time is directly related to the rotational velocity of the camshaft, which is driven by the crankshaft, and is therefore directly related to engine speed. Conventionally, this relationship is static and designed for a certain engine use.

Variable valve timing allows adjustment of the timing (i.e. adjustment of the phase *not* the duration) of opening and closing during engine operation and therefore optimization to specific engine demands[5]. The CO₂ emission reduction potential of variable valve timing is approximately 3%

3.1.3 Variable valve control

Variable valve control encompasses a series of technologies that allow (continuous) control over the valve actuation. Besides variable valve timing it includes technologies that enable control over the amount of lift of the valves, which implies control over the duration of the valve's opening and closing. Its reduction potential is estimated to be approximately 7%.

¹⁷ This is only an option for spark ignition engines because modern compression ignition engines already use direct injection.

¹⁸ There is some debate whether this will ever be a commercial option and no market introduction is yet foreseen.

¹⁹ http://www.mce-5.com/vcr_strategy/index.htm

3.1.4 Variable compression ratio

The compression ratio is conventionally fixed and limited by the maximum power output; as this requires the largest amounts of fuel to be burned and the combustion mixture cannot be compressed beyond a certain threshold before it starts to spontaneously detonate. At part load, however, this compression ratio is sub-optimal which leads to an inefficient energy transfer. Using a variable compression ratio allows the compression ratio to dynamically match variations in the required power output.[26] The GHG reduction potential can be estimated to be approximately 10%.

3.1.5 Direct injection

Direct injection in gasoline engines allows better control of the amount and timing of the fuel inlet in the combustion chamber. Also, the fuel mixture is more evenly dispersed and there is a slight cooling effect which allows for more aggressive timing of the combustion. This, together with the elimination or reduction of throttling or pumping losses allows a reduction potential of approximately 3-10%.

3.1.6 Downsizing

Downsizing, i.e. the reduction of engine volume while retaining the same power (which implies the need for a turbo), permits a reduction of the fuel consumption due to²⁰:

- Reduced pumping losses:
 - o Less volume swept on each engine revolution;
 - o Higher average load on driving cycle (higher average intake pressure).
- Gases-to-wall heat transfer reduction:
 - o Reduced internal surface area;
 - o Shorter flame travel distance (faster combustion>> reduced gases-wall heat exchange duration).
- Friction losses reduction:
 - o Smaller moving parts.

The mid-to-long term reduction potential may be estimated at approximately 10-20%.

3.1.7 Cylinder deactivation

Cylinder deactivation is the temporary reduction of an engine's capacity at low loads by using only some of the available cylinders. Because of its reduced capacity the engine will, even at low loads, operate close to its full (dynamic) capacity and will hence be more efficient. This is mainly because of reduced throttling or pumping losses. Cylinder deactivation, or 'variable displacement technology', offers a reduction potential of approximately 5% to 8% in engines with more than 4 cylinders. With lesser cylinders deactivation is not practical.[36].

3.1.8 Homogeneous charge compression ignition (HCCI)

Homogeneous charge compression ignition engines may be viewed as a sort of hybrid between spark ignition (SI) and compression ignition (CI) engines in as far as it uses a homogeneous combustion mixture as in SI engines but which is ignited using compression as in CI engines. The combustion process is hard to control but in theory diesel-like fuel consumption can be achieved with petrol-like pollutant emissions.

3.1.9 Fuel preference

Reduction of CO₂ emissions can also be achieved by shifting to fuels (and associated engine types) that have a higher efficiency (diesel) or lower CO₂ emissions per unit energy due to a lower C/H ratio (e.g. LPG and CNG)²¹. In Europe there has been a trend away from petrol fuelled

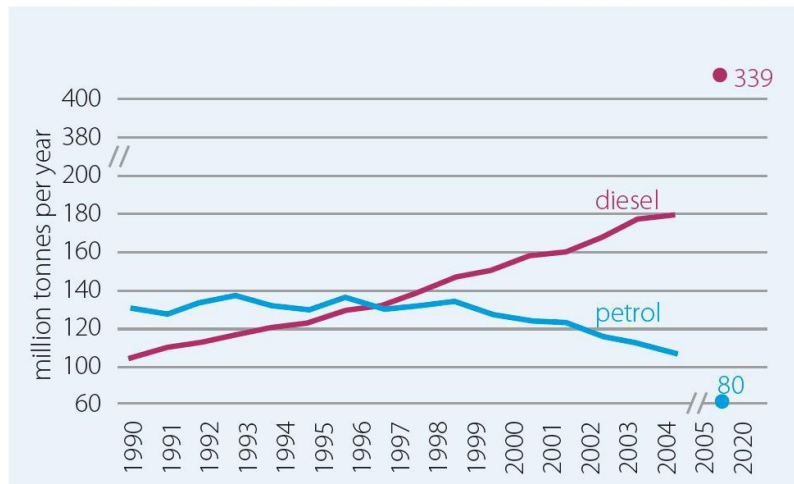
²⁰ http://www.mce-5.com/vcr_strategy/downsizing.htm

²¹ For example, LPG has Well-To-Wheel emissions that are 14% lower than a petrol-fuelled car and 10% lower than diesel.[7, 22]

vehicles toward diesel, which in itself already causes a decrease in GHG emissions on a per vehicle basis (Figure 9).

Whether one fuel is inherently more efficient than another, however, depends on how the combustion process is designed and how well it can be controlled. For example, diesel fuel is ignited by compression (compression ignition (CI)), whereas petrol is typically ignited using an electric discharge (spark ignition (SI)). As explained above, petrol in the concept of HCCI is ignited by compression and this allows diesel-like fuel efficiencies without sacrificing pollutant emissions.

Figure 9: Evolution of EU diesel and petrol demand. Figure reproduced from [7].



Source: Eurostat

Of course, biofuels, i.e. fuels derived from organic material, when efficiently produced have well-to-wheel GHG benefits. Biofuels, however, are subject of Paper 2 and will not be discussed here.

3.2 Options on the transmission

The transmission is a system that matches the required power at the wheels for any velocity of the vehicle with the engine's available rotational velocity and torque. From an emissions point of view a good transmission would always force the engine to run at its most efficient for its desired power output.

Options that are foreseen for the short to mid-term future are [33]:

- Optimized gearboxes
- Dual-clutch

Since hybridization also allows an optimized matching of the required power with the optimal position in the engine map (Section 2.2.1), stretching the definition somewhat, it may also be considered an improved transmission option.

3.2.1 Optimized gearboxes

Optimization of gearboxes may be estimated to offer a reduction potential of approximately 2% [33].

3.2.2 Dual-clutch

A dual-clutch transmission is essentially a system of two transmissions operating in parallel. It is set up in such a way that, using computerised hydraulics, one set of gears is always remains engaged during gear shifting. It allows much smoother transmission and by allowing continuous power flow from the engine to the transmission avoids deceleration (and subsequent acceleration) during the shifting of gears. This allows much smoother driving, which translates to a reduction potential of approximately 5%. In an automatic configuration, a fuel efficiency increase of 15% (compared to a conventional automatic transmission) is even claimed, mostly owing to avoidance of a torque converter²².

3.2.3 Hybridisation

A hybrid powertrain can be defined as any configuration that allows the use of energy from multiple energy sources, of which at least one is reversible (allowing storage of surplus energy). By combining the internal combustion engine with a storage device for energy from alternative sources (e.g. electricity or hydraulic energy) and one or more energy convertors (e.g. electric machines) that are capable of using this energy, various hybrid powertrain configurations can be realised. Generally, hybridisation is designed around an ICE/electric motor combination.

Several configurations are conceivable but a broad distinction is between parallel and series hybrids. In a parallel hybrid the electric motor and the ICE are installed so that they can both individually or together power the vehicle. Typically a small, efficient, ICE is the primary power source. When additional power is required, the ICE is supplemented by the electrical engine.

In a series hybrid all of the vehicle power output is determined by the actions of the electric motor. The ICE drives an electric generator instead of directly driving the wheels. The ICE is, thereby, decoupled from the vehicle speed, which enables an optimised choice of engine operating points and reduction of transient behaviour.

Upon braking, the electrical engine in both the parallel and series configurations can function as a generator, recovering braking energy to recharge the batteries. To a more limited extent, recuperation of braking energy can also be applied to vehicles with a conventional engine, e.g. using a flywheel.

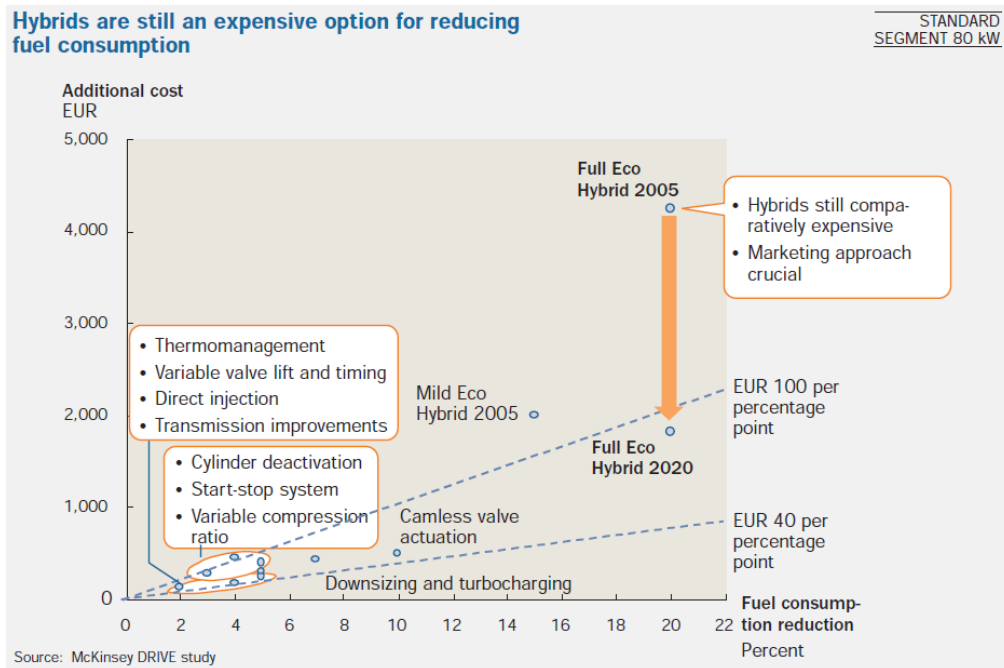
Another distinction can be made on the basis of the degree of electrification / hybridisation. Mild hybrids save fuel by shutting engine power off under most circumstances when the vehicle is stopped, braking, or driving / coasting at low speed. The engine restarts seamlessly and efficiently because the electrical engine is, in effect, an oversized starter motor. It can operate in parallel with the ICE but it has only limited propulsion power. Part-load operation of the ICE is further avoided by increasing the output power of the ICE and storing the excess power in the battery for later use. On the other end of this scale are full hybrids with electric motor power of the same order of magnitude as the ICE power. A further step in electrification is seen in plug-in hybrids. These vehicles have far more extensive all-electric drive capabilities. Their energy, however, is not only derived from on-board combustion of fuel but is supplemented by electricity from an external source.

Compared to advanced gear boxes, hybrid power trains offer further possibilities for optimising the engine operation with respect to efficiency. Efficiency improvements can be expected of some 10% - 25%, depending on powertrain configuration and level of hybridisation.

Although hybridization represents a large reduction potential, hybridization is a relatively expensive option (Figure 10).

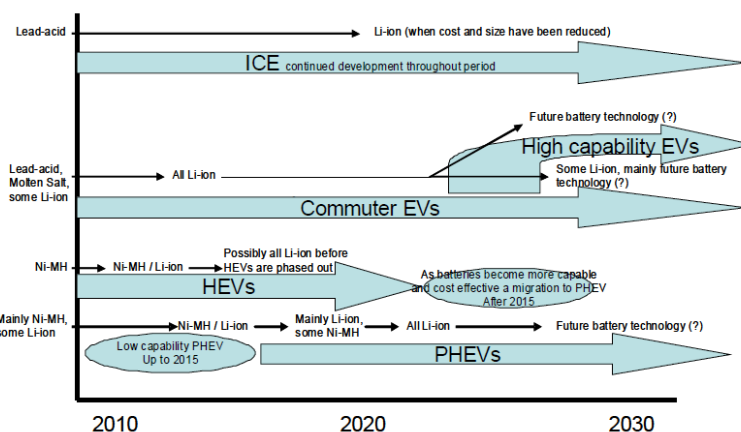
²² http://www.dctfacts.com/widc_pg3a.asp

Figure 10: Costs for reducing fuel consumption by means of hybridization versus improvements on the conventional drive train. (reproduced from [29])



For the time after 2020 some sources expect that the charge sustaining variant of hybridization may become completely replaced by the plug-in variant (Figure 11). As stated above, the plug-in variant draws part of its energy requirement from non-conventional sources and therefore this option will be discussed in Paper 2.

Figure 11: Time line for the introduction of electric vehicles with battery technology. (reproduced from [8])



Considering that the ICE in a hybrid vehicle will be downsized and considering that both hybridization and downsizing save fuel by allowing the ICE to run at its most efficient load, it makes sense to compare the reduction potentials and the costs of downsizing and hybridization (in the calculation this presents an 'either-or' choice). In doing so, it can be anticipated that a similar CO₂ reduction can be achieved using downsizing, for a much lower cost than by using hybridization. *These insights are new and subject to discussion.* Hybridization, however, should not only be judged on its own merits, but also as an enabler technology. Hybrid technology is expected to open up high voltage as a secondary network for vehicles, thus enabling high power applications [30]. These applications may increase or decrease energy consumption (the latter e.g. by allowing the shifting of power steering to, more efficient, electric operation).

3.2.4 Alternative powertrain options

Currently all hybrid vehicles on the market are electric-hybrid. It is, however, also possible to realise powertrain hybridisation using e.g. mechanical, pneumatic or hydrostatic energy storage.

4 Reducing the energy needed for propulsion and auxiliaries

4.1 Introduction

The loads on the vehicle consist of the force needed to accelerate the vehicle and the forces to overcome aerodynamic, gravitational and friction forces. In urban stop-and-go driving, aerodynamic forces play little role, but rolling resistance and especially inertial forces are dominant [23]. Conversely, at high velocities during highway driving aerodynamic losses become dominant.

Reducing inertial loads is accomplished by reducing vehicle weight, with improved design and greater use of lightweight materials. Reducing tyre losses is accomplished by improving tyre design and materials to reduce the tyres' rolling resistance coefficient, as well as by maintaining proper tyre pressure. Weight reduction also contributes, because tyre losses are a linear function of vehicle weight. Reducing aerodynamic forces is accomplished by changing the shape of the vehicle, smoothing vehicle surfaces, reducing the vehicle's frontal area, controlling airflow under the vehicle and other measures.

Not all the energy that is generated by the combustion engine is used for the propulsion of the vehicle. There are many secondary energy consuming components e.g. to assure basic requirements or to increase driver comfort (from electric car windows to heated driver's seats). These components may significantly affect the total energy consumption²³ and therefore improvements to their efficiency directly influence fuel efficiency (although these benefits may not be recognised on the type approval test for auxiliaries that are not switched on during the test).

4.2 Weight reduction

Weight reduction can be achieved by application of new materials (Table 2). In the mid-to-long term lightweight materials may be responsible for a reduction in car-body weight of up to 35% as is demonstrated in the FP6 SuperLIGHT-CAR project²⁴, while the long-term weight reduction potential of fiber-reinforced plastics, for example, may be as much as 60% [23].

Steel is currently the main material used in vehicles, averaging 70% of curb weight. It can be expected that in the mid to long term, steel will be increasingly replaced by high strength steel (allowing less material for a given construction), lightweight metals, such as aluminium or magnesium, or plastics and composites.

Table 2: Material costs and weight reduction potential of lightweight materials for 2008-2015 [35]

	Material cost [€/kg]	weight reduction [%]	weight reduction [kg/kg]	additional material costs [€/kg-replaced steel]
conventional steel	0.6	0	0	0
high strength steel	0.9	30	0.3	0.03
aluminium	2.0	40	0.4	0.6
glass fibre composite	3.0	30	0.3	1.5
carbon fibre composite	8.0	60	0.6	2.6
lignocellulosic fibre composite	2.0	30	0.3	0.8

²³ The energy consumption of mobile air conditioning systems, for example, are estimated to be 2.5%-7.5% of the total vehicle consumption.[23] Air conditioning, however, has a positive impact on the working environment of professional drivers and likely on the safe operation of the vehicle. It can, therefore, not easily be dispensed with.

²⁴ <http://www.superlightcar.com/public/index.php>

As the weight reduction potential of light-weight steel is rapidly approaching that of aluminium at lower costs, the main long term option taken into account in the assessment presented here is composites. The assumption is that carbon fibre composites have superior properties allowing their application in the vehicle body and other mechanically demanding structures.

It is assumed that glass and lignocellulosic fiber reinforced composites may be used for panels and for vehicle components with lower mechanical loads only. After 2015, large scale application may lead to reductions in material production costs (learning effects). The learning effects of composite materials, however, may be expected to be limited due to the need to open additional production lines when going beyond 50,000 (for carbon fibre reinforced composite) or 100,000 units (for glass fibre reinforced composite) annually. For this reason, steel - especially the high strength variants - may be expected to keep a significant share in the car body and structure.

The competitiveness of steel is expected to remain the strongest for the production of those components that can benefit from large volume production. This is because the costs for applying fibre reinforced plastic materials are strongly dependent on the production volumes. The fixed costs, which relate e.g. to the manufacturing machinery, are relatively low because the forces involved in shaping and tooling are relatively low. The variable costs, however, are relatively high because the materials costs are very high (~\$11/kg - \$22/kg compared to ~\$1.3/kg for steel in 2002 [11]) and the manufacturing is labour intensive. Conversely, the fixed costs for the manufacture of steel elements, which fibre reinforced plastics aim to replace, are relatively high. The variable costs, however, are relatively low because of the low costs for steel. Although other factors come into play, this illustrates why fibre reinforced plastics will become competitive first for small volumes, for which the fixed costs weigh heavily on the per unit costs, rather than for large volumes (Figure 12).

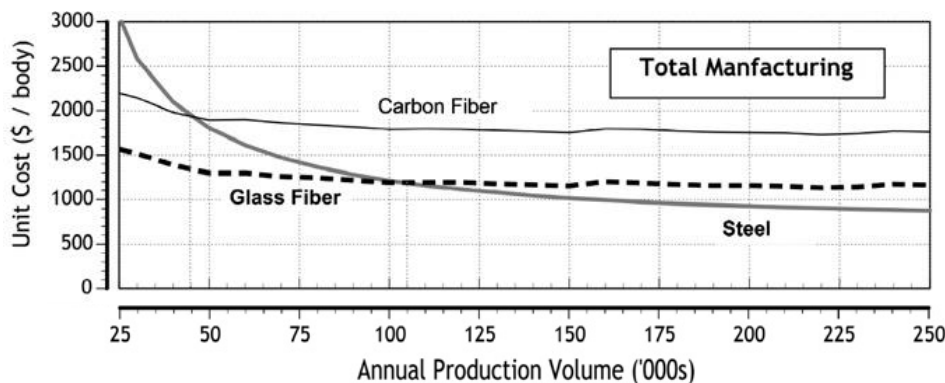


Figure 12: U.S. body-in-white production cost sensitivity to production volume for the total manufacturing costs. Figure reproduced from [18].

The development of lightweight materials does not necessarily lead to lighter vehicles since they may also be applied to increase the performance or safety of a vehicle for a given (or even increased) weight. Weight reduction per se, however, can be a very efficient measure in reducing GHG emissions. A 10% reduction in total vehicle weight reduces fuel consumption (and CO₂ emissions) by approximately 6.5% if engine power is also adjusted to keep the power-to-weight ratio (and thus the vehicle performance) constant. This holds for all road vehicles [23, 33, 35].

4.3 Improved aerodynamics

For light-duty vehicles, styling and functional requirements (especially for light duty trucks) may limit the scope of efficiency improvement to be gained by improved aerodynamics. The aerodynamic drag coefficient (CD) of heavy duty trucks may decrease by more than 50% when pneumatic blowing devices are used that stabilize the airflow around the trailers edges [23]. Note

that the blowing power can be obtained totally from the output of a turbocharger waste gate at cruise speed (i.e. no extra compressor power is required) [14]. For cruising speeds between 80 and 120 km/h the fuel consumption reduction is estimated to be 15% - 20%. Average real-world reductions will be smaller. For cars, improved aerodynamics may be expected to bring about 2% - 4% emissions reduction [25].

Since aerodynamic losses scale with the square of the velocity, reduced speed limits might be considered as a fuel conservation measure. Reducing speed limits, however, impacts on traffic flow and travel times, so that the impact must be assessed at a higher traffic system level than individual vehicles. This is outside the scope of this paper, all the more as changing speed limits is a policy option, and these are discussed in Paper 6.

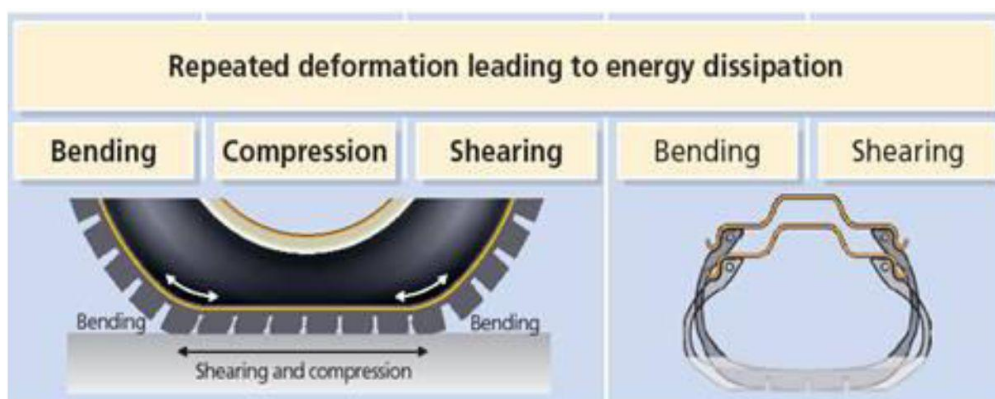
4.4 Low friction losses

Options to decrease friction losses typically reduce GHG emissions by a few percent and can already be implemented in the short term.

Tyre pressure monitoring systems

Rolling resistance is a function of the deformation of a tyre (Figure 13). When a tyre is insufficiently inflated these deformations will become larger and more energy is dissipated. A tyre pressure monitor (TPMS) helps the driver to keep tyres at the proper pressure and therefore avoids the extra fuel consumption resulting from otherwise increased rolling resistance.

Figure 13: Schematic representation of factors that determine the rolling resistance. Reproduced from [19].



Source: Barand and Bokar, 2008, SAE

Low rolling resistance tyres

Tyres have to comply with a manifold of design parameters, e.g. relating to safety, noise and durability. The application of low rolling resistance tyres (LRRTs) is therefore far from trivial, although recent studies have shown that there does not have to be a trade-off between safety and rolling resistance [9, 6]. Results of a Dutch measurement program, for instance, found tyres performing very well on rolling resistance and excellent on other tyre performance characteristics [15]. Penetration of LRRTs on the market can be facilitated by a labelling system [19, 32]. The reduction potential of LRRTs is estimated at 3% but it needs to be noted that low rolling resistance is also a function of the road quality, which falls outside the car manufacturer's span of control.

Low viscosity lubricants

Low viscosity lubricants decrease the friction losses in the drive train. The reduction potential is similar to that of LRRTs and TPMS and can amount to a few percent.

4.5 Waste heat recovery

Through high temperature exhaust gases and the engine's cooling system a lot of energy is emitted to the ambient atmosphere. Recapturing this thermal energy is a way of improving the overall fuel efficiency. Typical pathways for this recapture and reuse are:

- Heat exchange to a different heat carrier for:
 - heating of the car interior;
 - preheating the combustion mixture, which makes the cold start more efficient;
 - keeping the engine sufficiently warm (which is specifically beneficial in hybrids: when temporarily switched off during stop/start procedure)
 - refrigeration or air conditioning
- Conversion of heat to mechanical energy in order to:
 - assist the ICE with additional mechanical power;
 - (upon subsequent conversion to electric energy) power the battery and/or the vehicle's electric system
- Conversion of heat directly to electric energy (thermoelectric conversion) to:
 - power the battery and/or the vehicle's electric system

The currently most prevalent conversion principles are:

- Heat2power²⁵ “in-cylinder” heat recovery (expansion work)
- Rankine cycle (both steam and ethanol)
- Thermoelectric conversion (Seebeck effect)

The claimed efficiency is:

Heat2Power^{26,27}

- 15%-35% improvement in fuels savings under all driving conditions

Rankine

- From simulations (*Loughborough University* and *University of Sussex*):
 - 6.3% increased fuel efficiency for US06 Highway Drive Cycle
 - 31.7% increased fuel efficiency for US FTP-75 Urban Drive Cycle
- From *BMW*: With an organic Rankine cycle 10% fuel efficiency gain can be obtained at typical highway speeds (using both exhaust gas and cooling fluid for heat source)
- From *Honda*: With a Rankine cycle used for electricity generation a 3.8% fuel efficiency gain can be obtained when driving a constant speed of 100 km/h.

Thermoelectric conversion

- From *Volkswagen*: 600 W is possible for highway driving, this corresponds to 5% fuel efficiency improvement (the electric power could cover 30% of the average electrical power demand for passenger cars)
- From *BMW*: in a prototype 200 W has been demonstrated, which corresponds to 1% fuel efficiency improvement. A maximum attainable yield of 1 kW is expected.

4.6 Improving the energy efficiency of components

Some auxiliary components that consume significant power are:

- Air conditioners
- Lighting
- Power steering
- Aftertreatment systems

These options will be discussed briefly below.

²⁵ Heat2Power is the name of the company and will be onwards used to denote their proprietary technology.

²⁶ <http://www.greencarcongress.com/2008/11/waste-heat-reco.html>

²⁷ http://www.motorauthority.com/blog/1033090_french-company-claims-35-efficiency-improvement-with-thermal-energy-recovery-system

Mobile air conditioning systems (MACs) are a source of greenhouse gases not only because of their energy consumption but also because of the fact that some types of refrigerants are potent greenhouse gases, contributing to global warming when leaking from the MAC system. The EC aims at reducing greenhouse gas emissions from MACs by a ban on the refrigerant R134a, which has a high global warming potential (GWP)²⁸ of 1300, from all MACs from 2011 onwards for new vehicle models and from 2017 for all new vehicles [24, 23]. Also, directive 2006/40 requires that any new refrigerant must have a GWP below 150. It is expected that CO₂-based systems will become the dominant alternative and that these account for 100% of the new sales by 2014 or 2015 [33]. Eventually, however, it is up to the industry how to cope with the legislation and other options than CO₂-based systems are also feasible.

There is currently a trend toward very efficient LED lighting. It may be expected that on the short to medium term all vehicle lighting will be replaced by LEDs, which are typically 2-3 times as efficient as halogen bulbs [38].

Electrification would increase the efficiency of power steering because it allows power steering to become independent from the engine's power output. This, however, requires the availability of sufficient electrical power and thus significant levels of hybridisation.

²⁸ Global warming potential in CO₂ equivalents

5 Considerations for heavy goods vehicles

Freight transport by means of trucks is an important enabler for trade, commerce and economic growth in Europe. It is estimated that currently as much as 80% of the total quantity of goods is transported by trucks [12]. Options to reduce CO₂ emissions from heavy goods vehicles (HGVs) are largely the same as for light duty vehicles. There are, however, some special circumstances to be considered, which will be illustrated below.

5.1 Cost awareness in heavy duty transport

Fuel costs are a significant part of the operating costs of heavy duty vehicles. Therefore, fuel efficiency has always been an important design objective for HGVs and, consequently, the remaining CO₂ reduction potential is relatively small compared to the case of light duty vehicles. Manufacturers will always have an incentive for marketing new products, but there may be actions the European Commission can take to encourage innovation, such as reviewing/continuing/improving funding for R&D programs [17].

Because of cost awareness, fuel efficient driving may be expected to already be broadly employed by heavy duty drivers and further promotion of eco-driving may therefore be expected only to have a limited potential.

The potential for reducing idling emissions in HGVs, however, is found to be significant. In the U.S.A., a nationwide survey found that, on average, a long-haul truck consumed about 6,100 litres per year while idling during driver rest periods [23]. It has to be noted, however, that idling sometimes is purposefully used to provide cabin heating or to power auxiliary systems. For these purposes there should be alternatives for idling. This, nevertheless, indicates that behavioural practices could still save fuel in the heavy duty segment, despite an already high awareness of the costs associated with inefficient driving. Overall fuel savings from improved driver training may be estimated at 5% [17].

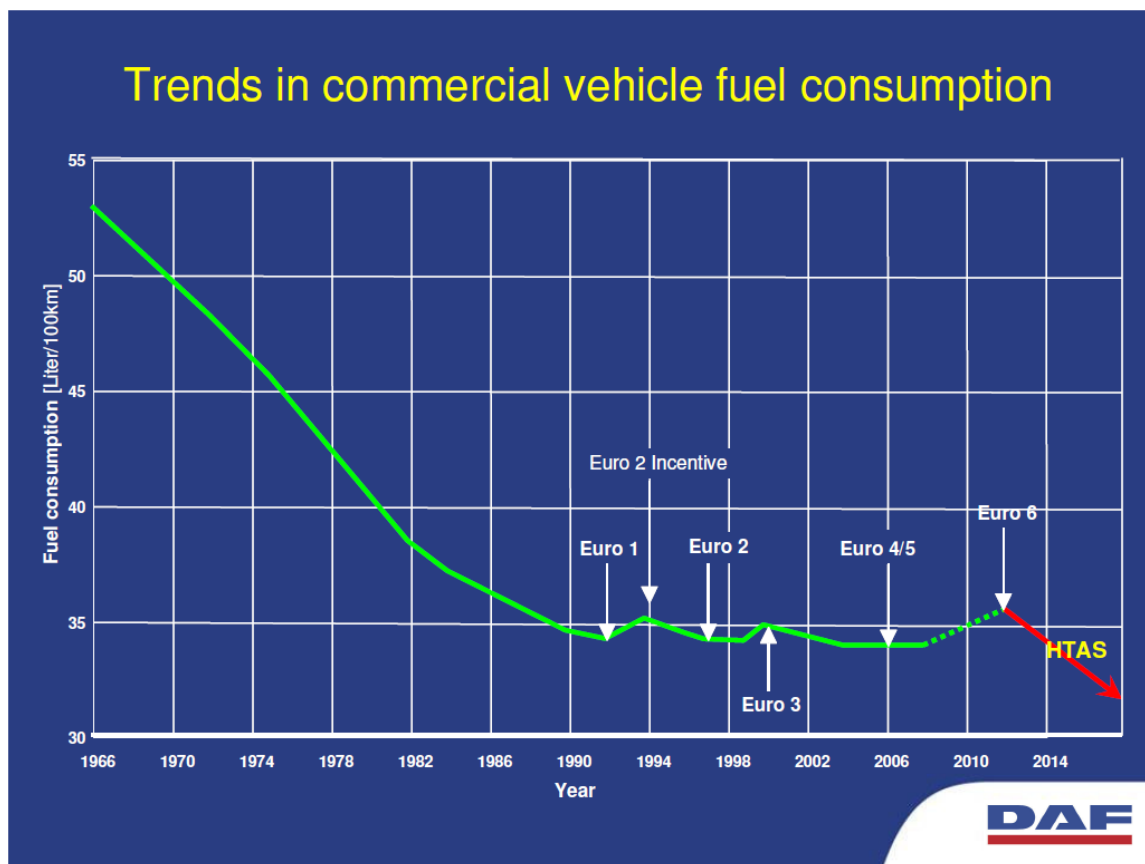
5.2 Effect of emissions legislation on fuel consumption

Figure 14 indicates that before the introduction of emissions legislation, fuel efficiency in HD vehicles has been steadily decreasing. The various technologies and engine adaptations that were introduced to comply with consecutive steps of exhaust emission legislation, however, correlate with an end to this downward trend in fuel consumption. Although this graph suggests that emissions legislation has a negative effect on fuel consumption, which is in principle true with a number of emission reduction measures, causality for the complete effect shown in Figure 14 is not self evident given the complexity of contributing factors that determine fuel consumption in heavy duty transport.

5.3 Effects of differences in transportation requirements

Engines in heavy duty applications are dimensioned at a lower power-to-weight ratio, and specifically in long haul transport, operate for a larger part of their time at high or full load compared to light duty vehicles. Therefore, the options that are listed for light duty applications that increase the efficiency at part load will represent a smaller contribution to the total reduction potential [34]. For urban distribution trucks and city buses, however, the driving pattern is generally more dynamic, so that engine improvements increasing part load efficiency and application of a hybrid power train may still offer significant fuel economy benefits.

Figure 14: Fuel consumption related to EU legislation (from [12]).



Vehicle elongation and increase of allowable vehicle weight (decreasing the number of vehicles per unit transported volume or weight and improving the aerodynamic characteristics of vehicles) only have effect for long haul transport. This is because drag losses are dominant only above a certain velocity and because most vehicles for urban distribution are usually not loaded to maximum capacity²⁹. The latter means that increasing the (allowable) capacity of urban distribution trucks does not necessarily decrease the number of vehicles per unit weight transported.

For HGVs, the CO₂ emissions on a per vehicle kilometre basis is not the most important parameter because options that decrease the per vehicle load capacity, with a constant transport demand, will lead to an increase of the number of vehicles. It is important to note that load capacity can be usefully expressed in load weight but also in load volume. Variations in these parameters do not necessarily have the same effect. Options that change the maximum cargo weight will not much influence the transport of volume intensive goods, whereas options that influence the allowable cargo volume will not much influence the transport of weight intensive goods. In heavy goods transport, therefore, it is also very important what the nature of the transported goods is.

The HGVs are usually designed to sustain the mechanical stresses of worst case usage. The actual stresses in long distance driving on highways, however, are lower for many components. This poses the possibility of designing special purpose long distance vehicles, in which the dimensions of the components are adapted to a lower mechanical stress level. In this way vehicle weight can be reduced. The costs of such specific vehicles would be much lower than the "lightweight" vehicles that would require specially developed lightweight materials and innovative design [24].

²⁹ The maximum utilization of city distribution vehicles is often limited to 50% [ACEA]

From these issues, it follows that the effectiveness of technological options depends very much on how a vehicle is used. It matters whether a vehicle is used primarily for urban distribution or for long haul transport and also whether the transported goods are volume intensive or weight intensive. In a broader perspective it even matters e.g. what the requirements in terms of delivery time are so as to be able to assess the feasibility of modal shift (i.e. shifting from road transport, e.g. to inland shipping or rail transport)³⁰. Vehicle specification, i.e. the tailoring of a vehicle to a specific task, can therefore be considered to be a technological option for GHG reduction. In a recent study for the European Commission by Faber Maunsell, the reduction potential of vehicle specification was rated 'high' (pooled together with improving a vehicle's aerodynamic properties)[17]).

5.4 Reduction options in HGVs

5.4.1 Engine and powertrain improvements

Similar to the options discussed in Chapter 3, options on the engine offer a potential for fuel consumption reduction. The reduction potential is estimated at approximately 5% [34].

5.4.2 Heat recovery

Approximately 50% of an HGV's fuel energy is expended as waste heat [28]. As described in section 4.5, heat recovery technologies can be used to improve the fuel economy. Since HGVs, because of their relatively high engine power, produce a relatively high heat flow, heat recovery technologies such as turbines may be used that are not easily feasible in passenger cars. Heat recycling technologies that increase engine efficiency by 5% will be on the road within the next five years. UK-based Clean Power Technologies has developed a system that uses waste heat to generate steam. It claims up to a 40% increase in fuel efficiency [28].

5.4.3 Low resistance tyres

As discussed in Chapter 4, low rolling resistance tyres can significantly add to the short term reduction potential. In the case of HGVs, low rolling resistance tyres can adopt the form of super wide tyres (super singles) in stead of pairs of conventional tyres. The estimated reduction potential is approximately 6% [34, 17].

5.4.4 Lightweight construction

In Section 4.2 it was argued that decreasing a vehicle's weight by using lighter and/or stronger materials has a direct relation with an increase in fuel efficiency. In Section 5.3, however, it was argued that this may not be the case for all types of heavy goods transport. For volume intensive goods transport, lightweight construction directly corresponds to lighter vehicles even at full load. For weight intensive vehicles, however, this is not the case. Here vehicle weight will be substituted by payload, so that emissions per vehicle km remain the same but decrease when expressed per tonne km. With this caveat in mind a reduction in fuel consumption of approximately 7% may be expected to result from application of lightweight construction [34].

5.4.5 Hybridisation

Hybridisation can have a significant effect for types of heavy goods transport with driving patterns that involve a lot of braking and accelerating and are therefore particularly effective in city buses and urban distribution trucks. An additional benefit of hybridisation is that regenerative braking reduces brake wear as a source of particulate matter emission.

The United States Department of Energy's National Renewable Energy Laboratory (NREL) has recently evaluated hybrid delivery vans of United Parcel Service (UPS).[27] For these parallel

³⁰ Modal shift is the topic of Paper 5.

hybrid UPS vans³¹ it was found that, in real world driving, they had, on average, a 29% greater fuel economy than equivalent diesel delivery vans (Figure 15). When evaluated on three urban test cycles in the laboratory³² the average fuel economy improvement was even found to be 31%-37%. This is consistent with the reduction potential of 39% fuel savings claimed by Hino for its Hybrid trucks for driving in urban environments with average speeds of 15 km/h.³³ This truck is in service with TNT Australia, who found, in real-world operating conditions, an actual reduction of 14% in CO₂ emissions when compared to conventional diesel trucks of equivalent size.³⁴

TNT Australia recently announced to double its Hino hybrid truck fleet.³⁵ Competitor DHL in the UK, which trialed the same vehicle, however, finds that the initial purchase price still outweighs the savings.³⁶ This illustrates the importance of the balance between costs and benefits of fuel saving technologies in commercial transport and how this, for the same technology, may differ between different operators. It must be noted that the operating costs of hybrid vehicles, apart from fuel consumption and the write-off on the initial investment, also include the costs for downtime, repairs and battery replacements.

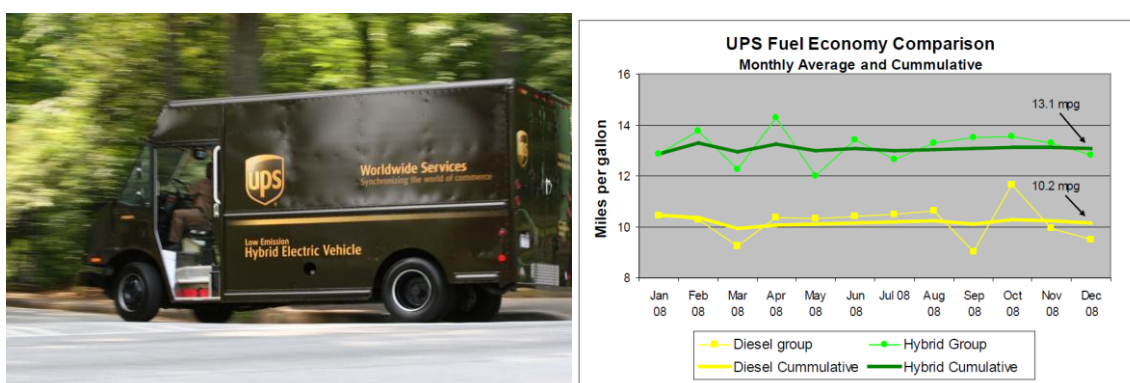


Figure 15: UPS hybrid delivery van and its average fuel consumption (10.2 mpg) compared to that of an equivalent diesel van (13.1 mpg) as determined in a recent RNEL 12 month trail. (Images reproduced from [27])

5.4.6 Reducing aerodynamic drag

A main cause for air drag is energy being dissipated in airflow turbulence. Therefore, the smoother the air flows around a structure, the less aerodynamic drag is observed. Airflow is more prone to become turbulent at higher velocities and when airflow is disturbed because of abrupt changes in the geometry (Figure 16). Aerodynamic drag, therefore, is increased for high velocities (even in the absence of turbulence because of increased viscous drag and pressure build-up in front of the vehicle) and is worse for truck/trailer combinations with abrupt changes in their geometry, i.e. sharp edges and (abruptly) protruding elements such as rear view mirrors.

³¹ Powered by an Eaton Corporation electric hybrid propulsion system.

³² Combined International Local and Commuter Cycle, West Virginia University City Cycle and Central Business District Cycle

³³ http://www.hino.com.au/Upload/specifications/hybrid/brochure/Hino_hybrid_8pp_brochure_FINAL.pdf, accessed February 11, 2010

³⁴ http://www.tnt.com/express/en_au/data/news/tnt_launches_australia.html, accessed February 11, 2010

³⁵ http://www.pressroom.com.au/press_release_detail.asp?clientID=31&prID=4050&navSectionID=2, accessed February 11, 2010

³⁶ The Hino Hybrid is priced at 60,500 AUD (approximately € 39,000,-). The Hino 300 Series 714 Hybrid is similar to the Hino 300 Series 716 Medium, which is also similarly priced

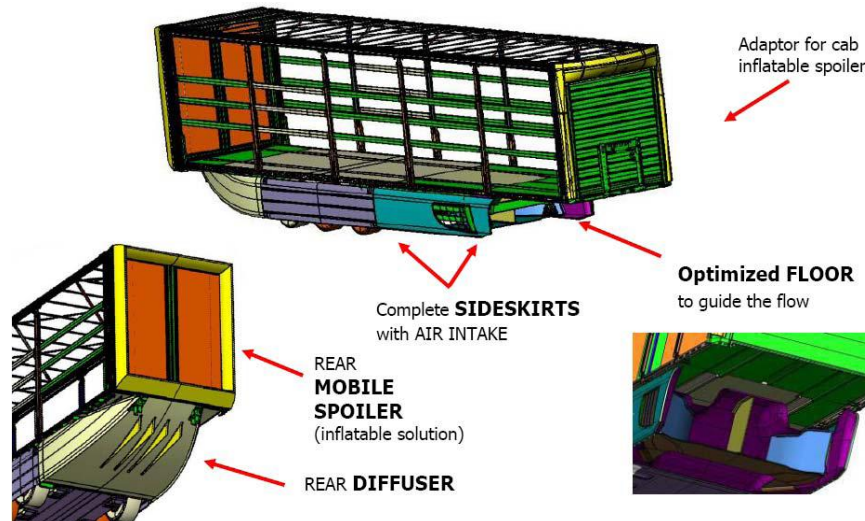
http://www.pressroom.com.au/press_kit_detail.asp?clientID=31&navSectionID=9&categoryID=1000&kitID=224, accessed February 11, 2010

Figure 16: Example of a truck/trailer combination in a wind tunnel³⁷. Specifically note the turbulent wake.



Some airflow disturbing elements cannot be avoided, e.g. a truck needs wheels and the truck and the trailer need to join somewhere. Considerable gains in aerodynamic efficiency can, nevertheless, be achieved by 'guiding' the airflow around these elements using e.g. rear wheel fairings to smooth the airflow around the rear wheels, under body panels that smooth air flow under the chassis, a roof deflector to direct air over the trailer, and a front air splitter incorporated into the front bumper to pass air around the truck (Figure 17). Other elements can be avoided altogether; the rear and side view mirrors e.g. can be replaced by cameras which have the additional advantage that blind spots can be eliminated. Using such improvements, the Innovation Truck concept by Daimler has recently shown a 3% fuel efficiency increase compared to an unmodified truck in wind tunnel tests³⁸.

Figure 17: Illustration of options to improve the aerodynamic properties of trailers (reproduced from [17]).



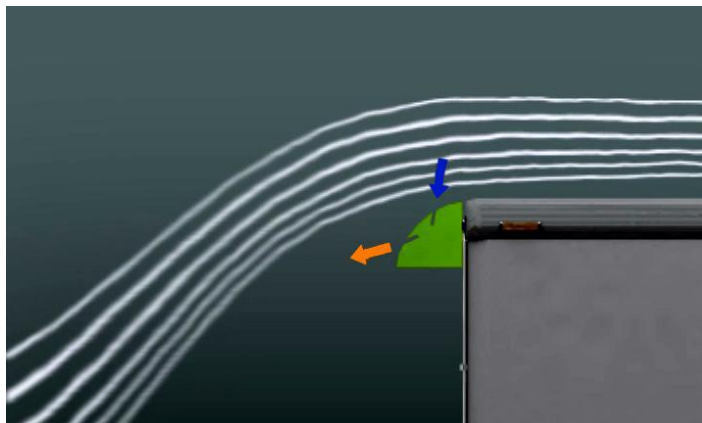
Most of the drag occurs at the rear of the vehicle where energy is dissipated in turbulence upon separation of flow (Figure 16). This separation can be delayed by avoiding straight edges but more efficiently, by gently blowing a jet of air over a specifically curved surface on the trailers edge to smooth airflow (Figure 18). This is called Active Flow Control (ACF) and it aims to improve fuel economy by 7-10%³⁹. On the short to medium term a total reduction in air resistance of approximately 6% may be expected [34].

³⁷ <http://www.donbur.co.uk/gb/aerodynamics.shtml>, accessed December 23, 2009

³⁸ <http://www.daimler-trucksnorthamerica.com/news/press-release-detail.aspx?id=805>

³⁹ <http://www.afctechnologies.com/default.php>

Figure 18: Schematic illustration of Active Flow Control (AFC).



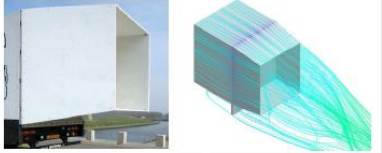




Other options are also conceivable but they might require changes in legislation. An example is a boat tail, which would require revision of the maximum allowable trailer length. A boat tail is a tapering – possibly hollow – rear end (Figure 19). The airflow follows the bodywork, resulting in a smaller wake and higher pressure at the rear, lowering the drag considerably.⁴⁰ Wind tunnel tests have shown that such boat tails can produce a drag reduction of 12%, which equates to a fuel saving of about 6%. Other such rear-end devices that reduce aerodynamic drag have similar reduction potential (Figure 20). These devices, under current law which sets a maximum to the length of the vehicle, would go at the expense of the trailer's loading capacity. It may, however, be possible to exempt these devices from the definition of HGV length without compromising current overarching policy objectives such as safety.[13]

Figure 19: A 'boat tail' prototype as developed by the Platform for Aerodynamic Road Transport (PART).



⁴⁰ <http://www.part20.eu/en/applications/container/>

Figure 20: Non-exhaustive overview of rear-end devices for the reduction of aerodynamic drag.
 Reproduced from [13].

Device	approx. additional dimension required	best suiting trailer type	approximate CO2 reduction long haul	Image / working principle
Open cavity tails	1.0 - 1.5 m	box, curtain, reefer, refrigerated box (reefer)	6%	
Inset open cavity tails	0.6 m - 0.8m	box, curtain, reefer, refrigerated box (reefer)	5-8%	
Inflatable open cavity tails	0.4 - 0.6 m	box, curtain, reefer, refrigerated box (reefer)	3-4%	
Inflatable closed cavity tails	1.0 - 1.5 m	box, curtain, reefer, refrigerated box (reefer), chassis	5%	
Active Flow Control / Difusors	0.3 m	box, curtain, reefer, refrigerated box (reefer)	7%	

5.5 Barriers to innovations

5.5.1 Time required for the adoption of innovations

Whereas the lifetime of a truck is 5 to 8 years, the lifetime of a trailer is up to 20 years. Therefore, new technology options have a long penetration time. This is specifically the case for aerodynamic and lightweight design aspects because they rely on truck-trailer integration.

5.5.2 Market barriers

Other barriers, specific to the HGV industry, are the high R&D costs per vehicle and the low truck market volumes. Also, for each tractor there are multiple trailers (four trailers to each tractor in the U.S. [28]). For this reason the trailers are idle most of the time and this reduces the payback from investments in the trailer development. Also, truck and trailer may have different owners and, whereas the trailer operator has a clear incentive to cut the fuel bill, this may not necessarily be the case for the trailer owner. Together with the razor thin margins in the trucking industry this makes it difficult to recuperate the R&D costs and investments in CO₂ reducing technologies. These costs are relatively high because of challenging reliability requirements and minimal technology cross-over from the cars market.

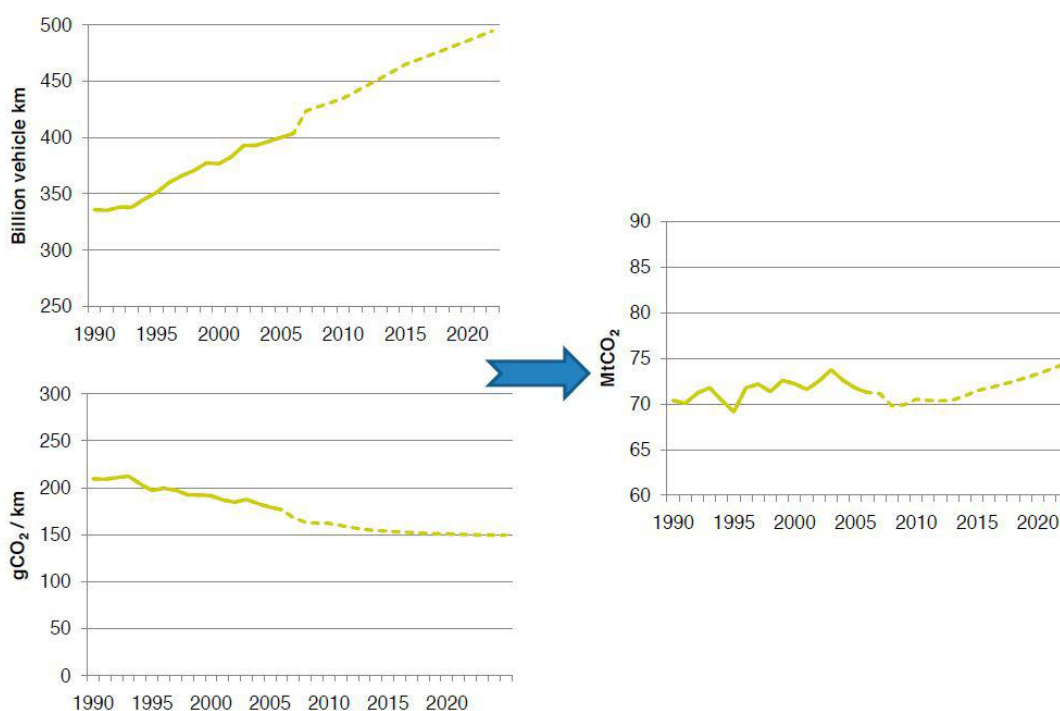
6 Assessment of measures

This section briefly assesses various options, discussed in previous sections, based on existing studies. The reduction potential, both for the short and the long term, and GHG abatement costs depend on the development of the reference situation. There is currently a trend toward increasing performance and luxury in passenger cars, leading also to higher weight. This is because these are attractive both from a consumer and the manufacturer's point of view [25]. Also, new vehicle legislation related to safety tends to result in increased weight of vehicles, and thus to more energy consumption, due to applied technical safety measures. This may, to some extent, be counteracted e.g. by including safety not in the vehicle design but in vehicle intelligence (ITS).

6.1 Long term overall reduction potential

The reduction that can be obtained on a vehicle level is partly offset by a trend toward more vehicle kilometres. This is illustrated for the UK situation in Figure 21, Figure 22 and Figure 23.

Figure 21: Historical trends and reference projections of vehicle-km, MtCO₂ and gCO₂/km for passenger cars. Graphs reproduced from [10].



Source: DfT, NAEI.

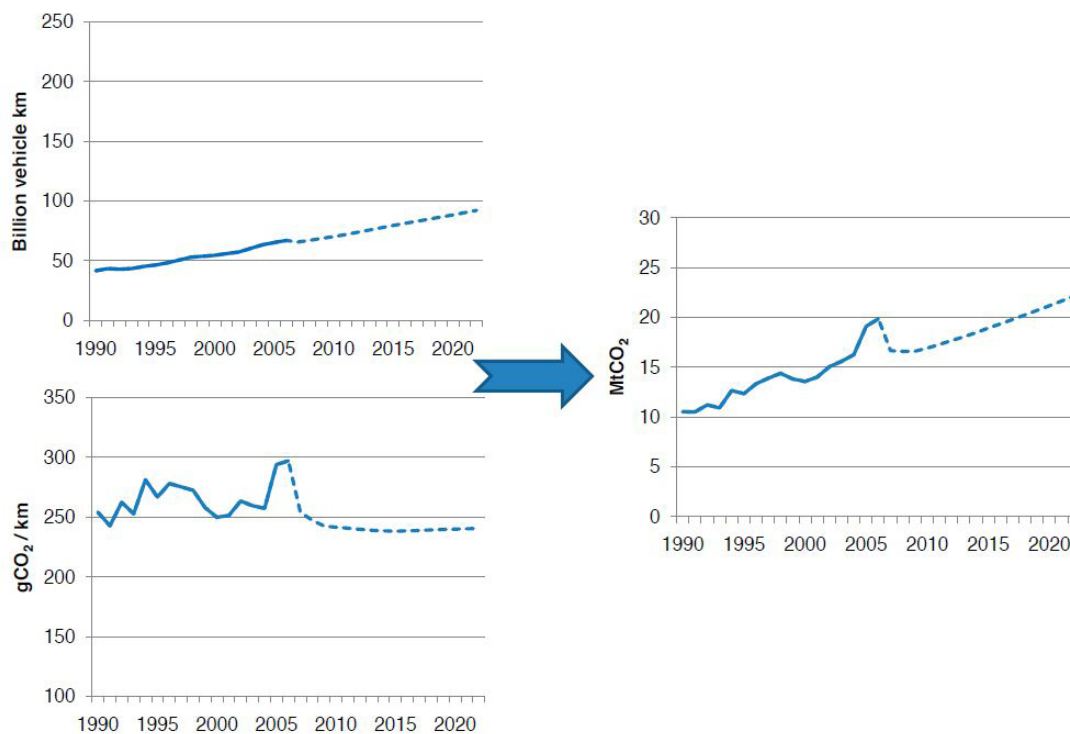
The obtainable long term emissions reduction by means of technical options on ICEs, excluding 'zero emissions' options⁴¹ such as biofuels and charge depleting hybridization, is eventually limited e.g. by the engine's maximum thermodynamic efficiency and the energy demands for accelerating the car's inertial mass. Where in practice the maximum reduction potential for ICE-powered vehicles lies is not clear, but there is consensus that in order to achieve ambitious long term GHG reduction targets⁴² there will be a need to also include zero emissions options such as

⁴¹ Zero emissions on a tank-to-wheel basis, i.e. excluding emissions from the production of alternative fuels or electricity.

⁴² To go, e.g. beyond 30% reduction in the UK,[25] or to achieve 40% reduction as is, according to a recent study by TNO feasible by 2040 in the Netherlands,[31] biofuels and electrification must be included.

vehicles running on biofuels or sustainably generated electricity or hydrogen in the fleet of the future. These options are the topic of Paper 2 [25, 31, 40].

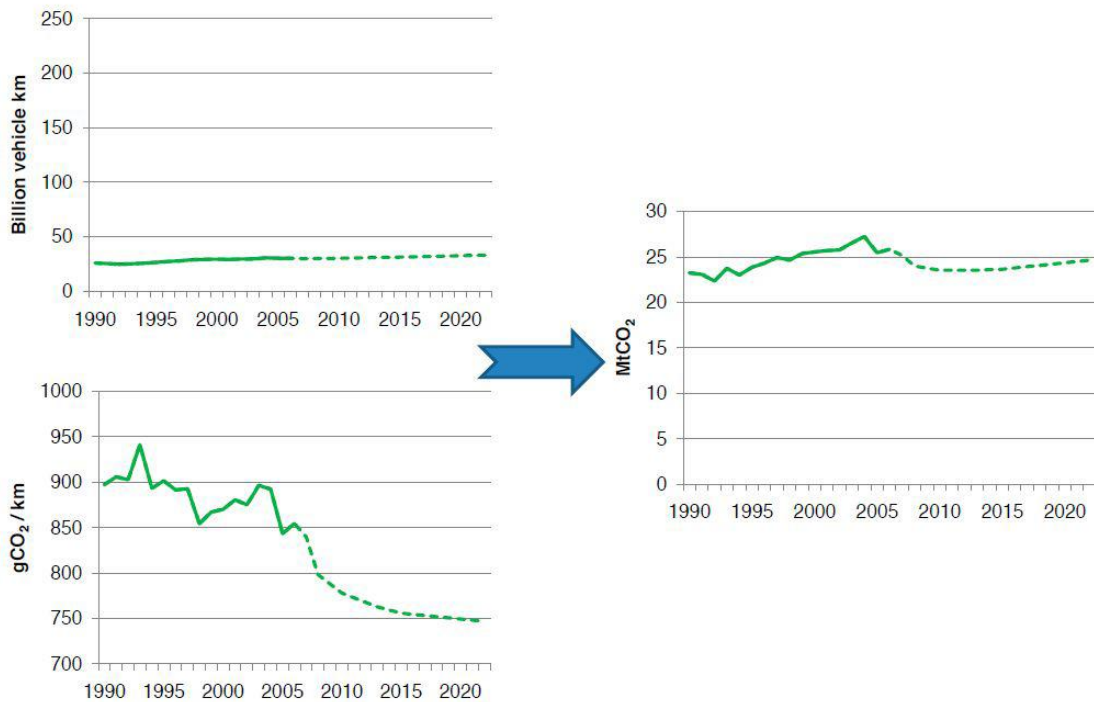
Figure 22: Historical trends and reference projections of vehicle-km, MtCO₂ and gCO₂/km for vans. Graphs reproduced from [10].



Source: DfT, NAEI.

Note: The jump in emissions is due to moving from historically recorded to modelled figures.

Figure 23: Historical trends and reference projections of vehicle-km, MtCO₂ and gCO₂/km for HGVs. Graphs reproduced from [10].



Source: DfT, NAEI.

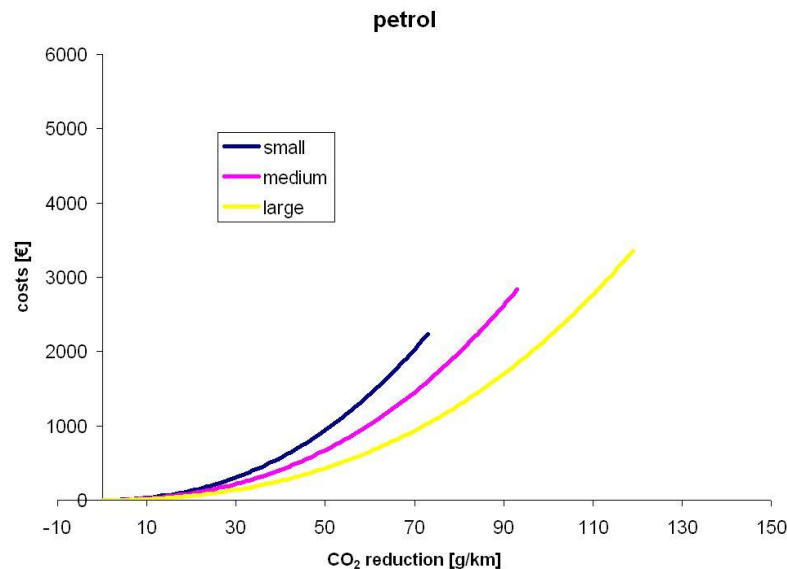
Note: Note the fall in projected gCO₂/km is due to moving from actual to modelled figures and use of biofuels; slower improvements from 2014 are due to the Euro fuel standards.

6.2 Costs at the vehicle level

The costs to arrive at a certain CO₂ reduction level are the sum of costs of the individual options that a manufacturer uses. Of course there are multiple 'packages' of technologies possible, but generally it may be expected that a manufacturer will choose the most cost efficient combination that meets a set of criteria which include customers demands and expectations that need to be satisfied⁴³. Generally, marginal costs increase with increasing GHG reduction levels. This dependency may be described using a non-linear cost curve (see examples in Figure 24 and Figure 25) [33, 37].

⁴³ Downsizing, e.g. is a relatively cheap but unattractive option for a sports car manufacturer. In stead he may choose the much more expensive option of using light weight materials.

Figure 24: Cost curves for petrol passenger vehicles, reproduced using the polynomials parameters as published in [37]. The maximum reduction potential is taken from unpublished work by TNO for the EC under ENV/C.5/FRA/2006/0071 because they were not explicitly included in the original publication.



The reduction potential for options on diesel engines is much more limited than that for options on petrol engines. The reason is that diesel engines are already relatively fuel efficient. For the same reason, the associated costs for attaining the same reduction are higher for diesel than for petrol. Since diesel powered vehicles are currently more fuel efficient than petrol powered ones, the emissions of a car fleet could be reduced if consumers could be influenced to choose for diesels. In the longer run, however, the effects of such a shift will diminish as the gap between petrol and diesel is likely to narrow over time due to the application of advanced efficiency improvement options [25].

More expensive are options on the combustion engine to dampen the effect of vehicle dynamics at the level of the engine so that it can continue to operate in its most efficient mode. This can be achieved in the easiest way and for the lowest cost for the vehicle use in which there is the lowest dynamics at the vehicle level, i.e. on the highways but, again, this has its limitations. Alternative CO₂ reduction technologies, namely hybridisation and electrification, also aim to remove the dynamic effects at the level of the engine but at higher cost and, arguably, with a higher net impact. This will be the most cost efficient only for vehicle applications in which there is the highest dynamics at the vehicle level, i.e. in the urban environment. From the above, it may therefore be reasoned that in the future a more explicit split in technology development for vehicles with primary urban or highway usage will occur.

The cost effectiveness of GHG reduction options can be graphically represented and compared in so-called marginal abatement cost curves (MACCs). For policy evaluation abatement costs are expressed as societal costs, exclusive of all taxes. Abatement costs can also be calculated from the end-user perspective. Due to the different share of taxes in vehicle price and fuel price the cost effectiveness from a societal perspective may differ from the end-user perspective. From the example of Figure 26, which is based on societal costs, it can be seen that for many options the lifetime fuel cost savings are higher than the additional vehicle costs (those options have a negative marginal abatement cost), but that their reduction potential is finite⁴⁴.

The costs presented here follow from *ex-ante* assessments. It is, however, known that these can differ very much from *ex-post* cost assessments. The only options that are discussed here are

⁴⁴ The abatement costs of compensated options are negative, which indicates that the extra costs of the technology are more than made up for by the total earnings, because of the technology, during the operational lifetime of the vehicle. The width of a plateau associated with a technology represents its reduction potential.

those that are presently known and of which sufficient information is available. Synergetic effects are not discussed for lack of information.

Figure 25: Cost curves for diesel passenger vehicles, reproduced using the polynomials parameters as published in [37]. The maximum reduction potential is taken from unpublished work by TNO for the EC under ENV/C.5/FRA/2006/0071 because they were not explicitly included in the original publication.

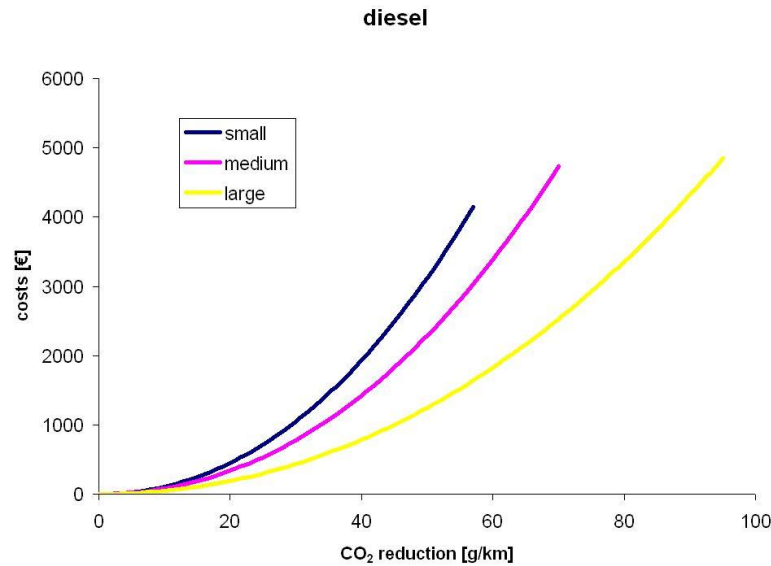
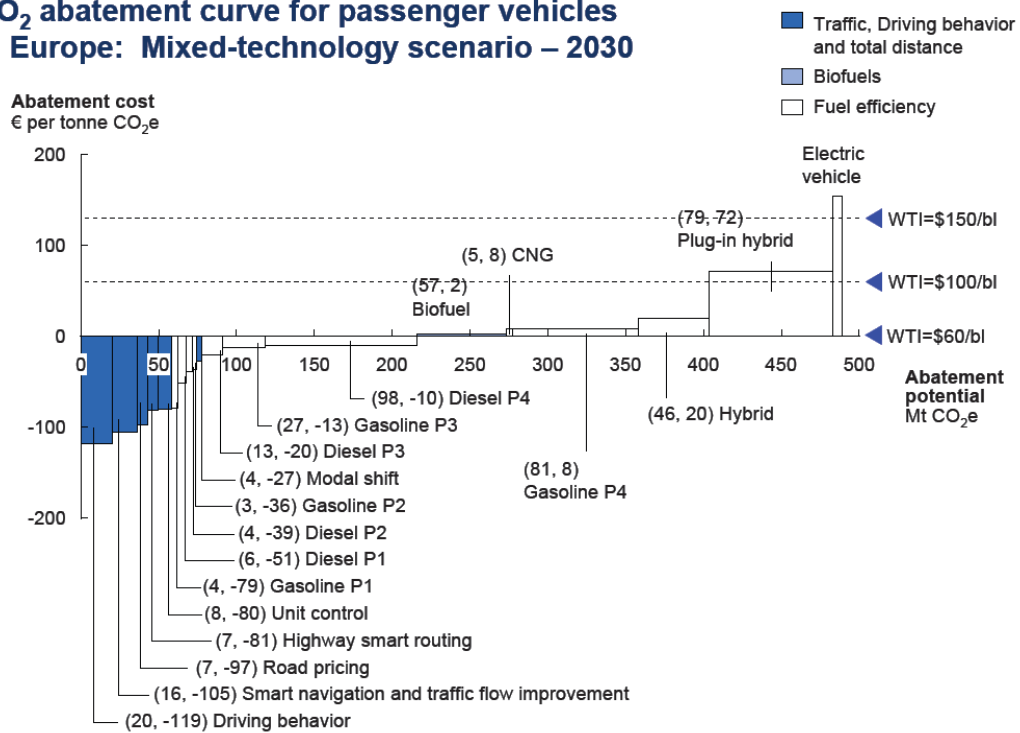


Figure 26: Marginal abatement cost curve for transport in Europe in 2030 (reproduced from [30]).

CO₂ abatement curve for passenger vehicles in Europe: Mixed-technology scenario – 2030



Source: McKinsey analysis

6.3 Timeframe and potential for application

The options discussed in this paper may be expected to achieve full market penetration by 2030. This means that from 2030 onward they do not contribute to the emissions reduction potential [20]. Many options, however, are potentially close to the market and, with the proper incentives, can significantly contribute by 2012-2015. Large scale application of advanced lightweight materials is probably not feasible on the short to middle long term but may contribute significantly by 2030.

Given the present popularity of electric and plug-in hybrid vehicles, it may be expected that charge sustaining hybrids will to a significant extent be replaced by plug-in hybrids by 2020.

6.4 Co-benefits

Generally and historically, research and development of new technologies in the automotive sector spill over to other sectors of the market. This may, therefore, also be expected for innovations with respect to fuel economy or other GHG emissions reducing options.

Clearly, another co-benefit of improving fuel economy is the reduced dependence on imported oil and therefore the security of energy supply may be expected to increase. Energy security is a topic in the 'Options' paper (<http://www.eurtransportghg2050.eu/cms/assets/Energy-security-paper-02-07-09.pdf>).

Some options, e.g. electrification, may reduce engine noise but this will be effective only for low velocities. At high velocities, noise is mainly determined by the vehicle's aerodynamic properties and by tyre noise. Because noise perception is on a logarithmic scale of sound energy, a high share of silent vehicles is necessary to achieve a noticeable reduction in perceived noise.

Reducing fuel consumption generally does not create synergetic effects with respect to pollutant emissions. The most fuel efficient vehicles are not necessarily also the cleanest vehicles. As a matter of fact large, non-fuel efficient vehicles, which usually have larger profit margins, can afford to have after treatment systems of better quality and consequently can be cleaner than smaller more fuel efficient vehicles. Some options, e.g. HCCI, do have a positive effect on pollutant emissions. This, however, will probably not directly affect air quality since air quality in Europe is mainly determined by emission standards. Where a CO₂ emission reduction option also reduces pollutant emissions, less after treatment will be needed to comply with these standards. The ability to use less complex (and generally less heavy) after treatment systems, however, offers monetary benefits to the manufacturer as well as indirect additional fuel savings.

6.5 Barriers

The infrastructure for innovations on conventional power trains is already in place and functioning. This also means, however, that manufacturers have already heavily invested in existing technology and are unlikely to be willing to switch to radically new technologies before these investments have been recouped. This delays the introduction of these technologies even when, from a technological maturity perspective, they are already close to the market. That is, of course, unless there is a self-contained market case, such as is generally the case in the HGV market.

Supply barrier

It is generally cheaper to increase the performance of a car than to increase its fuel efficiency. Because consumers also tend to favour more powerful cars over efficient ones it is currently more profitable and less risky to sell high performance [25].

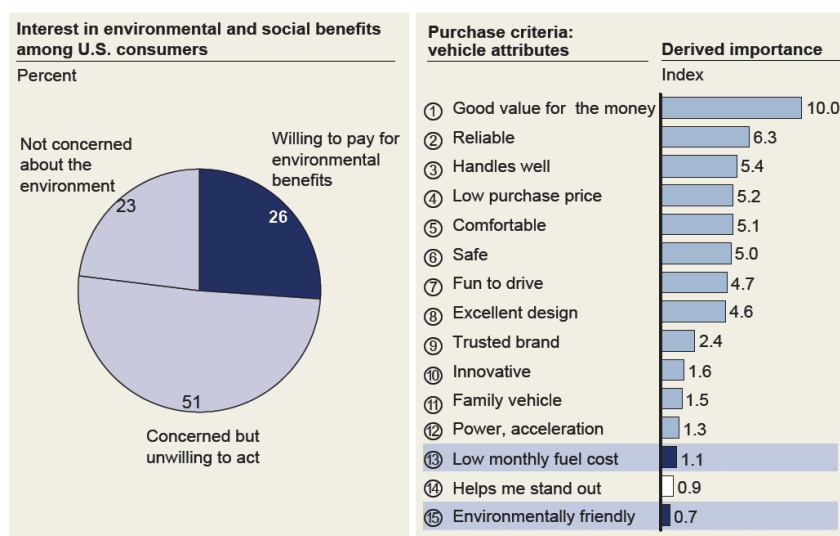
Demand barriers

Not all consumers are automatically willing to embrace fuel efficient vehicles. Consumers tend to rate short term costs and benefits, such as the purchase price of a vehicle and short term fuel

savings, higher than those on the long term (consumer myopia). Also, consumers have difficulty judging fuel consumption improvement with respect to their driving circumstances from only type approval data. There is, however, ongoing work to improve the test cycle to better correlate with real world driving while a labelling system could also help to guide consumers in their choices.

New technologies may be expected to succeed only if they meet consumer expectations. Note that the majority of the public is unwilling to pay for environmental benefits. This means that either the technology must be made available to the customer, at least initially, at comparable cost to conventional technology (i.e. heavily subsidized) or together with some benefit that offsets the cost difference (e.g. entitlement to tax savings) [30, 25]. In this view it is important to note that manufacturers cannot realize economies of scale if the demand is weak. Mandatory application by means of CO₂ emission standards is an alternative approach.

Figure 27: Role of CO₂ and fuel efficiency in vehicle purchases (reproduced from [30]).



Source: March 2008 McKinsey consumer survey; Synovate Motoresearch's Advanced Propulsion and Fuels Syndicated Study, 12/07, Consumer Survey – "How well does each statement below describe each of these vehicles"

7 Conclusions

The internal combustion engine determines the benchmark of what consumers expect from their vehicles in terms of behaviour, reliability and costs. Vehicles equipped with ICEs may be expected to continue to have a significant share among the propulsion systems for the various modes of road transport in the future. ICEs still have significant potential for efficiency improvement on a per vehicle basis and, therefore, the technological options to decrease GHG emissions from fossil fuel based road transport can have a significant effect on the overall reduction by 2050.

In improving the efficiency of an ICE-powered vehicle there are several 'strategies' that can be followed either in isolation or combined:

- Improvement of the combustion process
- Decrease of mechanical losses in the engine (friction and pumping losses)
- Decrease of mechanical losses in the transmission
- Decrease of inertial 'losses' (i.e. energy irreversibly expended to accelerate the vehicle's mass) and losses due to aerodynamic drag and rolling resistance
- Recuperation of energy (e.g. kinetic energy upon braking or waste heat from the exhaust)
- Reduction of energy demand from peripheral processes (i.e. by improving the efficiency of auxiliary components)

Many options will result in improved part-load efficiency and dampening of the effect of driving dynamics on the engine efficiency. Because of this, fuel efficient driving will become less effective.

Many options can be implemented in the short to medium term. Although the options to achieve demanding CO₂ reduction targets on the vehicle level will always be expensive in first instance, full penetration of these options may be expected by 2030, and therefore by 2050 significant cost reduction because of learning effects may be expected.

Hybridization is an interesting option with respect to opening new pathways toward fuel consumption reduction as it involves progressive electrification of the power train or of auxiliary processes. Hybridisation *per se*, however, is an expensive option compared to further improvements of the conventional power train, which offers similar reduction potential but which can be achieved at lower cost. Also, whereas hybridization should be viewed in the light of enabling energy saving options that rely on the availability of sufficient electrical power, the reverse is equally true (i.e. the availability of more on-board electric energy may also lead to application of additional energy *consuming* features).

Weight reduction may significantly contribute to fuel efficiency improvement if the weight advantage is not used to increase vehicle performance or to enable added safety features. Safety measures in general will lead to an increase in mass and fuel consumption. This may be countered by including safety not in the vehicle design but in the vehicle intelligence. Friction losses from rolling resistance or sub-optimal lubricants contribute a few percent to the fuel consumption. LRRTs, TPMS and low viscosity lubricants can therefore increase the reduction potential by an equal few percent. A few percent can also be gained by recuperating waste heat energy. A few percent of reduction potential can furthermore be gained from improving the energy efficiency of components. Specifically noteworthy are mobile air conditioners (MACs) that do not only contribute to the GHG emissions by way of their energy consumption but also because of possible leakage of their refrigerant. In the near future, however, it is mandated that MACs will be operated with low global warming potential refrigerants.

Whereas the importance and the potential of GHG reduction measures for passenger transport have been studied relatively well, much less is known about heavy duty vehicles. External stimulation of improvements in heavy duty fuel efficiency is also less urgent because fuel consumption in the heavy duty segment is to some extent self regulated because fuel consumption constitutes an important part of the operational costs in heavy goods transport. Factors that stand in the way of a full optimisation of fuel efficiency are e.g. related to the

complexities of ownership and to variations in the vehicles' use and therefore to differences in optimisation requirements. For example, because of the typical life span of trailers, the options on the trailer design (such as lightweight construction and aerodynamic design) will have a long penetration time. Moreover, there may not be an incentive for improving the trailers with respect to its associated fuel consumption when the costs thereof must be borne by the trailer owner whereas the benefits for reducing the fuel bill will be collected by the truck owner.

Because the effectiveness of technological options depends very much on how a vehicle is used, a more explicit split in vehicle technology, thereby tailoring the options for fuel consumption reduction to the specific use of the vehicle, may become apparent in the future. Changes in legislation may also support an increase in the extent of fuel efficiency options, for example by allowing an increase in the maximum load or length of heavy duty vehicles or by diversification of the safety requirements for urban and highway transport.

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