EU Transport GHG: Routes to 2050?

Development of a better understanding of the scale of co-benefits associated with transport sector GHG reduction policies

Charlotte Brannigan (AEA)
Gena Gibson (AEA)
Nikolas Hill (AEA)
Michael Dittrich (TNO)
Arno Schroten (CE Delft)
Huib van Essen (CE Delft)
Anouk van Grinsven (CE Delft)

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Contact details

Nikolas Hill
AEA
The Gemini Building, Fermi Avenue
Harwell, Didcot
OX11 0QR
United Kingdom

T +44 (0)870 190 6490
E EUTransportGHG2050@aeat.co.uk
E Nikolas.Hill@aeat.co.uk

Ian Hodgson
Transport and Ozone Unit
Climate Action Directorate General
European Commission
CLIMAC.2 Brussels
Belgium

T +32 (0)2 298 6431
E Ian.Hodgson@ec.europa.eu

Project

www.eutransportghg2050.eu

Partners

www.aeat.co.uk
www.cedelft.nl
www.tno.nl
www.tepr.co.uk
Executive Summary

To be completed for final version.
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Glossary

BAU  Business as usual, i.e. the projected baseline of a trend assuming that there are no interventions to influence the trend.

BEV  Battery electric vehicle, also referred to as a pure electric vehicle, or simply a pure EV.

Biofuels  A range of liquid and gaseous fuels that can be used in transport, which are produced from biomass. These can be blended with conventional fossil fuels or potentially used instead of such fuels.

Biogas  A gaseous biofuel predominantly containing methane which can be used with or instead of conventional natural gas. Biogas used in transport is also referred to as biomethane to distinguish it from lower grade/unpurified biogas (e.g. from landfill) containing high proportions of CO₂.

Biomethane  Biomethane is the term often used to refer to/distinguish biogas used in transport from lower grade/unpurified biogas (e.g. from landfill) used for heat or electricity generation. Biomethane is typically purified from regular biogas to remove most of the CO₂.

CNG  Compressed Natural Gas. Natural gas can be compressed for use as a transport fuel (typically at 200bar pressure).

CO₂  Carbon dioxide, the principal GHG emitted by transport.

CO₂e  Carbon dioxide equivalent. There are a range of GHGs whose relative strength is compared in terms of their equivalent impact to one tonne of CO₂. When the total of a range of GHGs is presented, this is done in terms of CO₂ equivalent or CO₂e.

DG TREN  European Commission’s Directorate-General on Transport and Energy. This DG was split in 2009 into DG Mobility and Transport (DG MOVE) and DG Energy.

Diesel  The most common fossil fuel, which is used in various forms in a range of transport vehicles, e.g. heavy duty road vehicles, inland waterway and maritime vessels, as well as some trains.

EEA  European Environment Agency.

EV  Electric vehicle. A vehicle powered solely by electricity stored in on-board batteries, which are charged from the electricity grid.

FCEV  Fuel cell electric vehicle. A vehicle powered by a fuel cell, which uses hydrogen as an energy carrier.

GHGs  Greenhouse gases. Pollutant emissions from transport and other sources, which contribute to the greenhouse gas effect and climate change. GHG emissions from transport are largely CO₂.

HEV  Hybrid electric vehicle. A vehicle powered by both a conventional engine and an electric battery, which is charged when the engine is used.

ICE  Internal combustion engine, as used in conventional vehicles powered by petrol, diesel, LPG and CNG.

Kerosene  The principal fossil fuel used by aviation, also referred to as jet fuel or aviation turbine fuel in this context.

1 Terms highlighted in bold have a separate entry.
**Lifecyle emissions**

In relation to fuels, these are the total emissions generated in all of the various stages of the lifecycle of the fuel, including extraction, production, distribution and combustion. Also known as **WTW emissions** when limited specifically to the energy carrier/fuel.

**LNG**
Liquefied Natural Gas. Natural gas can be liquefied for use as a transport fuel.

**LPG**
Liquefied Petroleum Gas. A gaseous fuel, which is used in liquefied form as a transport fuel.

**MtCO₂e**
Million tonnes of CO₂e.

**Natural gas**
A gaseous fossil fuel, largely consisting of methane, which is used at low levels as a transport fuel in the EU.

**NGV**
Natural Gas Vehicle. Vehicles using natural gas as a fuel, including in its compressed and liquefied forms.

**NOₓ**
Oxides of nitrogen. These emissions are one of the principal pollutants generated from the burning of fossil and biofuels in transport vehicles.

**Options**
These deliver GHG emissions reductions in transport and can be technical or non-technical.

**Petrol**
Also known as gasoline and motor spirit. The principal fossil fuel used in light duty transport vehicles, such as cars and vans. This fuel is similar to aviation spirit also used in some light aircraft in civil aviation.

**PHEV**
Plug-in hybrid electric vehicle, also known as extended range electric vehicle (ER-EV). Vehicles that are powered by both a conventional engine and an electric battery, which can be charged from the electricity grid. The battery is larger than that in an HEV, but smaller than that in an EV.

**PM**
Particulate matter. These emissions are one of the principal pollutants generated from the burning of fossil and biofuels in transport vehicles.

**Policy instrument**
These may be implemented to promote the application of the **options** for reducing transport’s GHG emissions.

**TTW emissions**
Tank to wheel emissions, also referred to as direct or tailpipe emissions. The emissions generated from the use of the fuel in the vehicle, i.e. in its combustion stage.

**WTT emissions**
Well to tank emissions, also referred to as fuel cycle emissions. The total emissions generated in the various stages of the lifecycle of the fuel prior to combustion, i.e. from extraction, production and distribution.

**WTW emissions**
Well to wheel emissions. Also known as lifecycle emissions when limited specifically to the energy carrier/fuel.
1 Introduction

1.1 Topic of this paper

This paper is one of a series of reports drafted under the EU Transport GHG: Routes to 2050 II project. These papers provide the results from each of the primary eight tasks from the project and will form the basis for chapter in the final report. This paper focuses on a better understanding of the scale of co-benefits associated with transport sector GHG reduction policies.

1.2 The contribution of transport to GHG emissions

Transport is responsible for around a quarter of EU greenhouse gas emissions making it the second biggest greenhouse gas emitting sector after energy (see Figure 1.1). Road transport accounts for more than two-thirds of EU transport-related greenhouse gas emissions and over one-fifth of the EU's total emissions of carbon dioxide (CO₂), the main greenhouse gas. However, there are also significant emissions from the aviation and maritime sectors and these sectors are experiencing the fastest growth in emissions, meaning that policies to reduce greenhouse gas emissions are required for a range of transport modes.

Figure 1.1: EU27 greenhouse gas emissions by sector and mode of transport, 2007

![Graph showing greenhouse gas emissions by sector and mode of transport, 2007]

Source: EC DG Energy (2010)³

Notes: International aviation and maritime shipping only include emissions from bunker fuels

While greenhouse gas emissions from other sectors are generally falling, decreasing 15% between 1990 and 2007, those from transport have increased by 36% in the same period. This increase has happened despite improved vehicle efficiency because the amount of personal and freight transport has increased.

In the run-up to the Conference of the Parties of the UN Framework Convention on Climate Change in December 2009, the leaders of the EU's Member States called for significant reductions in global greenhouse gas (GHG) emissions:

“The European Council calls upon all Parties … to agree to global emission reductions of at least 50%, and aggregate developed country emission reductions of at least 80-95%... It supports an EU objective, in the context of necessary reductions according to the IPCC by developed countries as a group, to reduce emissions by 80-95% by 2050 compared to 1990 levels.”

The key role that transport has to play in this long-term economy-wide aspiration was underlined by European Commission President Barroso in his Political Guidelines for the next Commission where he emphasised the need to maintain the momentum towards a low carbon economy and towards decarbonising the transport sector in particular. In March 2010, the Commission, as part of its Europe 2020 strategy, announced that it would make proposals to decarbonise transport, and in doing so linked the need to decarbonise transport with the wider sustainable growth agenda.

These high level political statements set the framework within which the original EU Transport GHG: Routes to 2050 project was undertaken. One of the main aims of this project was to provide information and analysis to assist the Commission with its early thinking on a co-ordinated approach to reducing the GHG emissions of all modes of transport.

The increasing political importance that is being attached to decarbonising transport reflects the fact that, of all the economy’s sectors, transport has proved to be one of the most problematic in terms of reducing its GHG emissions. As mentioned earlier, since 1990, GHG emissions from transport, of which 98% are carbon dioxide (CO₂), had the highest increase in percentage terms of all energy related sectors. Furthermore, transport’s GHG emissions are predicted to continue to increase, without additional measures, to over 2,000 MtCO₂e by 2050. This increase is shown in Figure 1, with a split by mode of transport. The figure is an output from an Excel-based illustrative scenarios tool (IST) called SULTAN (SUstainable Le TRANsport), which was developed under the previous project in order to identify the GHG reductions that transport could potentially deliver by 2050.

An increase of the order projected in Figure 1 would leave transport’s GHG emissions 74% higher in 2050 than they were in 1990 (when the sector’s emissions were nearly 1,200 MtCO₂e) and around 25% above 2010 levels. Significant emissions increases between 2010 and 2050 are projected for road freight (for which an increase of more than 45% is projected), aviation (more than 50%) and maritime (more than 65%) without additional policy instruments. Whilst GHG emissions from cars are still projected to contribute the most to the sector’s GHG emissions in absolute terms in 2050, their emissions are projected to have declined slightly from 2010 levels, as anticipated improvements in the energy efficiency of vehicles negate projected increases in demand.

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5 Barroso, J (2009) Political Guidelines for the next Commission, September 2009, Brussels
Figure 1.2: Business as usual projected growth in transport's GHG emissions by mode

![Total Combined (life cycle) GHG emissions, BAU-a](image)

**Source:** SULTAN Illustrative Scenarios Tool, developed for the EU Transport GHG: Routes to 2050 project

**Notes:** International aviation and maritime shipping include estimates for the full emissions resulting from journeys to EU countries, rather than current international reporting which only include emissions from bunker fuels supplied at a country level (which are lower).

Figure 1.2 shows the baseline, as projected by SULTAN. This is consistent with the range of results from other models and tools, although many of these only project to 2030\(^8\). Clearly, the predicted continued growth in the EU-27’s GHG emissions from transport has the potential to prevent the EU meeting the long-term GHG emission reduction targets that the European Council supports, if no action is taken to reduce these emissions.

Figure 1.3 demonstrates that on current trends, transport emissions could be around 30% of economy-wide 1990 GHG emissions by 2050\(^9\). Whilst simplistic, in that it assumes linear reductions, the figure demonstrates that there is clearly a need for additional policy instruments to stimulate the take up of technical and non-technical options that could potentially reduce transport’s GHG emissions. The EEA believes that all available policy instruments need to be used to achieve the ambitious GHG reduction targets\(^10\).

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\(^8\) See Appendix 19 SULTAN: Development of an Illustrative Scenarios Tool for Assessing Potential Impacts of Measures on EU transport GHG for details of the assumptions used and approach taken in the SULTAN Illustrative Scenarios Tool to projecting business as usual GHG emissions; also see [http://www.eutransportghg2050.eu](http://www.eutransportghg2050.eu).

\(^9\) The emissions included in this figure – for both the economy-wide emissions and those of the transport sector – include emissions from international aviation and maritime transport, in addition to emissions from “domestic” EU transport.

1.3 Background to the project and its objectives

EU Transport GHG: Routes to 2050 II is a 15-month project funded by the European Commission's DG Climate Action and started in January 2011. The context of the project is still the Commission's long-term objective for tackling climate change. The scope of the first project was very ambitious, and the outputs from the study were very detailed and have already proved to be of great value to the European Commission and to industry, governmental and NGO stakeholders. However, there were a number of topic areas where it was not possible within the time and resources available for the study team to carry out completely comprehensive research and analysis. In particular, as the project evolved, both the study team and the Commission Services became aware that there were a number of themes and topic areas that would benefit from further, more detailed research. This new project is a direct follow-on piece of research to the previous EU Transport GHG: Routes to 2050 study, building on the research and analysis carried out for that study and complementing other work carried out for the forthcoming Transport White Paper. In particular, the outputs from this new study will help the Commission in prioritising and developing the key future policy measures that will be critical in ensuring that GHG emissions from the transport sector can be reduced significantly in future years.

Therefore, the key objectives of the EU Transport GHG: Routes to 2050 II are defined as to build on the work carried out in the previous project to:

- Develop an enhanced understanding of the wider potential impacts of transport GHG reduction policies, as well as their possible significance in a critical path to GHG reductions to 2050.

Further develop the SULTAN illustrative scenarios tool to enhance its usefulness as a policy scoping tool and carry out further scenario analysis in support of the new project;

Use the new information in the evaluation of a series of alternative pathways to transport GHG reduction for 2050, in the context of the 50-70% reduction target for transport from the European Commission’s Roadmap for moving to a competitive low carbon economy in 205012;

As before, given the timescales being considered, the project will take a quantitative approach to the analysis where possible, and a qualitative approach where this is not feasible. The project has been structured against a number of tasks, which are as follows:

- **Task 1**: Development of a better understanding of the scale of co-benefits associated with transport sector GHG reduction policies;
- **Task 2**: The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions;
- **Task 3**: Exploration of the knock-on consequences of relevant potential policies;
- **Task 4**: Exploration of the potential for less transport-intensive paths to societal goals;
- **Task 5**: Identification of the major risks/uncertainties associated with the achievability of the policies and measures considered in the illustrative scenarios;
- **Task 6**: Further development of the SULTAN tool and illustrative scenarios;
- **Task 7**: Exploration of the interaction between the policies that can be put in place prior to 2020 and those achievable later in the time period;
- **Task 8**: Development of a better understanding of the cost effectiveness of different policies and policy packages;
- **Task 9**: Stakeholder engagement: organisation of technical level meetings for experts and stakeholders;
- **Task 10**: Hosting the existing project website and its content;
- **Task 11**: Ad-hoc work requests to cover work beyond that covered in the rest of the work plan.

As in the previous project, stakeholder engagement is an important element of the project. The following meetings are being scheduled:

- A large stakeholder meeting was held in on 29th June 2011, at which this project was introduced to stakeholders, along with the presentation of interim results.
- A series of four Technical Focus Group meetings. The first two were held on 4th May 2011. The next two will be held on 28th November 2011.
- A second large stakeholder meeting at which the draft final findings of the project will be presented and discussed, anticipated to be held in February 2012.

As part of the project a number of papers will be produced, all of which will be made available on the project’s website in draft and then final form, as will all of the presentations from the project’s meetings.

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1.4 Background and purpose of the paper

The objective of this paper is to better understand the scale of co-benefits associated with transport sector GHG reduction policies.

Objective:
- To develop a better understanding of the air quality, energy security, environmental noise, and health co-benefits associated with possible transport sector GHG reduction policies

Outputs:
- Develop a better understanding of air quality co-benefits
- Estimates of the energy security implications of different abatement options, using new quantitative data for the key assessment criteria
- Development of an understanding of the noise co-benefits of specific relevant GHG abatement policies
- Understanding of the health co-benefits of specific GHG abatement policies
- Identification of the relative values of the different co-benefits
- A paper presenting the task findings from all of the above, which will also form the basis of a chapter in the final report.

The research that our team carried out during the ‘EU Transport GHG: Routes to 2050?’ study indicated that the co-benefits of policies to reduce transport sector GHG emissions could be significant, and that there was a need to carry out further work in this area. During the previous study, we carried out some initial work on energy security issues (presented in Report I – “Energy Security and the Transport Sector”) as well as developing calculation functionality within the SULTAN tool that allows users to examine the impacts of transport-sector GHG policies on emissions of NOx and particulate matter. However, as the study progressed, it became clear that further analysis of co-benefits would be useful, and in particular, it would be useful to be able to quantify these co-benefits as far as possible. The Commission has a requirement for more detailed information on the co-benefits associated with transport sector GHG reduction policies. In particular, there is a need to be able to quantify the co-benefits associated with GHG reduction policies, and as far as possible build in additional functionality into the SULTAN illustrative scenarios tool so that a wider range of co-benefits can be quantified when analysing GHG reduction policies (the latter aspect to be dealt with in Task 6). The Commission is also interested in gaining an understanding of the relative values of the different co-benefits, and we have developed an outline approach for tackling this issue.

Analysis of the co-benefits of GHG reduction policies is an increasingly important area of research as it is becoming clear that co-benefits can be very important in helping to make the economic case for GHG abatement measures. During the previous research project, our team carried out initial research on some of the key co-benefits, but there was not the time available within the study to carry out detailed quantitative analysis of all of the issues.

The majority of the co-benefits associated with GHG reduction policies for the transport are directly related to health, including:
- Improved air quality due to reduced emissions of air pollutants from transport;
- Reduced ambient noise levels due to quieter low-carbon vehicles (e.g. electric vehicles);

\[13\] Reduced climate change itself can also have various health benefits. However, since these are related to the primary aim of climate policy, these should not be labelled as co-benefits.
- Reductions in the number and/or severity of traffic accidents (e.g. through speed reduction policies);
- Increases in the amount of physical exercise carried out by the population in general due to a shift to non-motorised transport modes (cycling and walking); and
- Indirect effects related to the life cycle effects of vehicles, energy carriers or infrastructure.

For each of these effects, two mechanisms can be distinguished. The first one is the way GHG policy for transport induces these effects. The second is the impact these effects have on human health. In order to understand the health impacts of these policies, both mechanisms should be assessed.

### 1.5 Structure of the paper

Following this introduction this paper is structured according to the following further 6 chapters:

**Section 2. Air Quality:** Development of a better understanding of the air quality co-benefits of GHG reduction policies, including: an understanding the likely air quality impacts of full penetration of Euro 6/VI vehicles in the European fleet; an insight into the indirect air quality emissions from production of electricity and hydrogen for locally–zero emission vehicles; air quality emissions from hybrid vehicles in type approval and real world; air quality emissions of biofuels used in transport; air quality emissions of a range of non-technical GHG policy measures; non-exhaust air pollutant emissions, including brake and tyre wear; more in-depth quantitative exploration of potential overall impacts of a limited number of selected GHG reduction options on overall air pollutant emissions from transport.

**Section 3. Environmental Noise:** Providing a better understanding of the environmental noise co-benefits of GHG reduction policies for road and railways.

**Section 4. Energy Security:** Developing a better understanding of the energy security co-benefits of GHG reduction policies, including: Building upon the initial energy security issue analysis undertaken in the ‘EU Transport GHG: Routes to 2050?’ study, and as far as possible, undertake a full quantification of the energy security implications of potential transport sector abatement options.

**Section 0. Health:** Developing a better understanding of the health benefits of GHG reduction policies, including: the number and severity of traffic accidents (e.g. through speed reduction policies); and physical exercise carried out by the population in general due to a shift to non-motorised transport modes (cycling and walking).

**Section 6. Indications of the relative values of the different co-benefits:** Developing indications of the relative values of the different co-benefits, including: Development of a semi-quantitative method for comparing the relative values of co-benefit, and taking account evidence on the scale of importance of each co-benefits to the wider community of the EU.
2 Air Quality Co-benefits of GHG Reduction Policies

**Objectives:**
The purpose of this sub-task was to:

- Develop a better understanding of the air quality co-benefits of GHG reduction policies, including:
- An understanding the air quality impacts of full penetration of Euro 6 vehicles in the European fleet;
- An insight into the indirect air quality emissions from production of electricity and hydrogen for locally–zero emission vehicles;
- Air quality emissions from hybrid vehicles in type approval and real world;
- Air quality emissions of biofuels used in transport;
- Air quality emissions of a range of non-technical GHG policy measures;
- Non-exhaust air pollutant emissions, including brake and tyre wear;
- More in-depth quantitative exploration of potential overall impacts of a limited number of selected GHG reduction options on overall air pollutant emissions from transport.

**Summary of Main Findings**
⇒ To be added when the chapter is completed after the November Focus Group Meeting.

2.1 Introduction

Transport-related air pollutant emissions are a major cause of health and environmental problems. Poor air quality can increase the risk of cardiopulmonary disease, respiratory symptoms and allergy development. An estimated 100,000 deaths per year are caused in Europe by urban air pollution, to which transport is a major contributor (WHO, 2011). The tailpipe emissions from road transport of most concern include nitrogen oxides (NO\(_x\)), sulphur dioxide (SO\(_2\)) and fine particulate matter (PM). NO\(_x\), SO\(_2\) and particularly PM emissions are harmful to human health. SO\(_2\) and NO\(_x\) emissions are also the main causes of acid deposition, which leads to changes in soil and water quality and damage to vegetation, buildings and aquatic life (EEA, 2011a). Other air pollutant emissions from transport include carbon monoxide (CO) and hydrocarbons (HC). CO reduces oxygen in the bloodstream and can cause breathing difficulties and cardiovascular effects. HC reacts with NO\(_x\) in sunlight to form ground-level ozone (smog) which can cause breathing difficulties. HC and NO\(_x\) also react to form fine PM. Inhaling particulate matter has been linked to asthma, lung cancer, cardiovascular problems, birth defects and premature death. Non-tailpipe emissions from road transport occur from tyre and brake wear, which contributes to the coarse fraction of particulate matter (PM\(_{2.5}\) to PM\(_{10}\)).

The main driving forces to reduce emissions of these pollutants have been EC Directives on vehicle emission and fuel quality. Vehicle emissions are regulated by the Euro standards, which have been successively tightened over the years. The most recent Euro 5 and 6 standards for light duty vehicles (Regulation EC 715/2007) set limits on emissions of NO\(_x\), PM, CO and HC from new vehicles from 2011/2012 (Euro 5) and 2015/2016 (Euro 6). They also introduce standards on durability, on-board diagnostics, vehicle repair and maintenance information. Emissions of these pollutants from heavy duty vehicle (HDV) engines are regulated under a corresponding set of standards, with the forthcoming Euro VI standard...
(Regulation EC 595/2009) due to be mandatory for new HDVs from 2013. Fuel quality is regulated by the original Fuel Quality Directive (FQD, 98/70/EC) and a series of subsequent amendments, which set mandatory specifications for motor fuels. The FQD has led to a direct reduction in emissions from vehicles consuming these fuels by limiting the content of sulphur, benzene and aromatics, and by limiting summer fuel vapour pressure. Additionally, the FQD has facilitated indirect emissions reductions by enabling the use of new and improved emission control technologies. Examples include selective catalytic reduction (SCR), diesel particulate filters (DPF) and other catalyst systems. This has mainly been possible through the reduction of fuel sulphur content in petrol and diesel fuels, in particular with the mandatory introduction sulphur-free fuels from 2005 in road transport and 100% conversion by 2009. Directive 2009/30/EC has recently amended the FQD and covers sustainability criteria for biofuels and vapour pressure waivers for fuels containing bioethanol.

A parallel series of emission directives has been established for non-road mobile machinery (NRMM), which also covers the rail and inland shipping transport modes. Directive 2004/26/EC set reduced emission limits for NO\textsubscript{x}, PM, CO and HC from new machinery engines in stages up to Stage IV (2013/14). The directives addressing fuel quality for fuels used by NRMM also complement the emission directives. The sulphur content of fuels used in rail and inland shipping is now also controlled under the latest FQD amendment (2009/30/EC), with the sulphur content of diesel fuels used in rail and inland waterways being harmonised with those for road transport in the next few years.

Maritime shipping emissions are regulated by the IMO with MARPOL 73/78 (the International Convention on the Prevention of Pollution from Ships) Annex VI setting limits on NO\textsubscript{x} and SO\textsubscript{x} emissions from ship exhausts. However, the provisions appear to have had relatively little impact on improving the specific emissions of maritime shipping over the last decade. In the EU marine fuels are controlled under the Sulphur Content of Marine Fuels Directive (SCMFD, 2005/33/EC), amending Directive 1999/32/EC, and internationally under MARPOL.

As a direct result of the legislation referenced, the specific emissions of air pollutants from passenger and freight transport have generally decreased during the time period 1995-2010 for the majority of transport modes and especially for passenger transport, as illustrated in Figure 2.1. The highest reduction of specific emissions can be observed in the road sector following the implementation of successive Euro emission standards, which has led to significant reductions in most pollutants (Figure 2.2) and improvements in local air quality. However, total transport reductions have been offset to a degree by rapid growth in the maritime transport sector (particularly for sulphur where fuel content is several orders of magnitude larger than for other modes).
There is significant potential for synergistic climate change and air quality benefits to be achieved via the application of certain transport sector GHG abatement options. In the previous ‘EU Transport GHG: Routes to 2050?’ study, an initial analysis was undertaken to determine the likely scale of NO\textsubscript{x} and PM co-benefits that could be achieved. The SULTAN illustrative scenarios tool provides quantitative data on the effects of GHG abatement measures on the direct emission of these air pollutants. However, a more comprehensive understanding of the scale of air pollutant co-benefits is needed.
2.2 Review of development with respect to air pollution emissions from transport

Conventional vehicles are a ‘moving target’ with respect to emissions of air pollutants and CO₂. The introduction of Euro 6/VI - and possibly even Euro 7/VII or beyond – will ensure very low emission levels from conventional vehicles. Full penetration of these higher Euro standards will therefore substantially reduce air quality problems in Europe. As a consequence of this, the local air quality benefits of zero emission may diminish as conventional cars become cleaner. However, there are important related considerations for this analysis, discussed further in this section.

Figure 2.3 provides an illustration of the penetration into the passenger car fleet of vehicles complying with successive Euro standards. In the passenger car market, adoption of the latest standards by new models ahead of the deadline is more common. The Euro 5 standards for passenger cars were mandatory from 2009. By 2010, 10% approximately of the petrol car fleet and 13% of the diesel car fleet as modelled in the TREMOVE model comply with this standard. In the case of petrol cars, which have the same emission limits for Euro 5/6, fleet penetration rises to 72% by 2020 and 95% in 2030. Euro 6 standards for diesel cars will enter into force in 2014. Fleet penetration of Euro 6 vehicles will reach 38% in 2020 and 86% in 2030. Euro 5 and 6 diesel vehicles combined reach 75% in 2020 and 93% by 2030. Therefore, although new vehicles which adhere to more stringent emission limits take some time to penetrate the fleet, by 2020 three-quarters of the total European passenger car fleet is expected to be Euro 5 standard or higher. By 2030, over 90% of vehicles will be Euro 5 or higher. The pollutant emission factors per km would be expected to decline accordingly with this trend.

Figure 2.3: Estimated penetration of Euro standards into European passenger car fleet

Equivalent data from TREMOVE also suggests that by 2020, 38% of vans (including light trucks) will be Euro 5 standard and 33% Euro 6. By 2030, 31% of vans will be Euro 5 and 57% Euro 6 (see Figure 2.4). This is a significantly lower rate of penetration than for cars, due to lower overall rates of fleet turnover in TREMOVE for such vehicles.

Technological improvements have historically penetrated both the commercial van and heavy truck fleet at a slightly lower rate than for passenger cars. At least for the heavy trucks fleet, this is because of a higher sensitivity to fuel consumption (which comprises a significant
proportion of operational costs), and there is a trade-off between fuel efficiency and air pollutant emissions control. Therefore, due to the penalty on fuel efficiency, the Euro standards tend to be adopted much closer to the deadline (i.e. as late as possible) for the majority of truck models. Euro VI standards will take effect from 2013. Assuming that all new vehicles sold after 2013 are compliant with Euro VI, by 2020 56% of heavy trucks will be Euro VI, rising to 85% in 2030. This does not account for imports of older vehicles from outside of Europe therefore actual uptake of Euro 6 vehicles is likely to be slower, as for vans.

Figure 2.4: Estimated penetration of Euro standards into European commercial road fleet

Source: TREMOVE model & study team calculations
Notes: EU-27 countries (excludes Norway, Switzerland, Turkey & Croatia); data for Euro VI are not included in the TREMOVE model – penetration rates were estimated assuming that all new vehicles entering the fleet after 2013 would be Euro VI. Retirement rates for Euro V vehicles were adjusted to match retirement rates for Euro IV vehicles. Any remaining imbalance in totals was reconciled by assuming the oldest vehicles were retired first. This result is approximate only. The data for buses shows some irregularities which are transferred from the TREMOVE model.

The fleet penetration scenarios from TREMOVE suggest that the higher Euro standards take several years to gain significant market share. However, the inevitable retirement of older vehicles means that their share will tend to grow, and by 2020 Euro 5/V vehicles (or higher) are likely to represent around three-quarters of the European vehicle fleet. By 2030, Euro 6/V are expected to account for the vast majority (around 90%) of vehicles. Consequently, the relative gains of carbon abatement technologies in terms of their co-benefits for air quality are likely to diminish in line with the penetration of the higher Euro standards.

However, although road transport emissions have decreased over the past decades as a result of successive Euro standards, the reductions achieved for certain pollutants could arguably have been larger on the basis of the regulatory requirements on new vehicles. The results of ambient monitoring show that the trend in decreasing emissions is at a somewhat lower rate than expected based on national inventory reporting, particularly in urban areas (ETC/ACC, 2011). Over recent years, it has been found via experimental measurements that the real on-road emissions of pollutants such as NO\textsubscript{x}, hydrocarbons, CO, and primary PM from vehicles often can exceed the regulatory emission limits as specified in the Euro emission standards for each vehicle type. This is particularly the case for NO\textsubscript{x} emissions from Euro 3/III and 4/IV diesel vehicles (passenger, and light- and heavy-duty vehicles). There are already indications that higher real driving emissions for diesel vehicles are also a problem for Euro 5/V and may be a problem for Euro 6/IV.

Research carried out in the UK has considered evidence from analysis of vehicle remote sensing data (Defra, 2011), in addition to ambient monitoring. The results of this work
suggests that in urban conditions - at least for light duty diesel vehicles (cars/vans) - there has been little change in total NO\textsubscript{x} emissions over the past 15 years or so. This is consistent with earlier research from two German technology institutes that reported similar findings (T&E, 2006). The Defra (2011) work found that for HGVs NO\textsubscript{x} emissions appear to have only improved after Euro IV (after which they decreased by about one third). Also of concern was the finding that selective catalytic reduction (SCR) used on HGVs appears to be ineffective under urban-type (slow speed, low engine temperature) conditions. However, Euro VI legislation will include a specific slow speed driving cycle that would be expected to address this issue. A summary of the most recent Euro standards applicable for heavy duty vehicle engines is provided in Table 2.1.

### Table 2.1: EU Emission Standards for HD Diesel Engines, g/kWh

<table>
<thead>
<tr>
<th>Tier</th>
<th>Date of mandatory introduction for new vehicles</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro IV</td>
<td>October 2005</td>
<td>1.5</td>
<td>0.46</td>
<td>3.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Euro V</td>
<td>October 2008</td>
<td>1.5</td>
<td>0.46</td>
<td>2.0</td>
<td>0.02</td>
</tr>
<tr>
<td>Euro VI</td>
<td>January 2013</td>
<td>1.5</td>
<td>0.13</td>
<td>0.4</td>
<td>0.01</td>
</tr>
<tr>
<td>Euro VI</td>
<td>% reduction on Euro IV</td>
<td>0%</td>
<td>0%</td>
<td>-43%</td>
<td>0%</td>
</tr>
<tr>
<td>Euro VI</td>
<td>% reduction on Euro V</td>
<td>0%</td>
<td>-72%</td>
<td>-80%</td>
<td>-50%</td>
</tr>
</tbody>
</table>

The reasons for this situation are complex, but can be summarised as being due to differences between ‘real’ driving conditions and the ‘traditional’ driving test cycle used to assess compliance of vehicles with emission standards. The test cycle, by design, must be of a limited duration and must allow a high degree of reproducibility and repeatability across a wide range of measurement laboratories. This encourages manufacturers to optimise the emission performance of vehicles for the test cycle rather than for real on-road driving conditions. The lower-than-expected performance of the Euro standards is contributing substantially to the difficulties many Member States face to attaining both their national NO\textsubscript{x} emission ceilings (EEA, 2011b) and NO\textsubscript{2} air quality limit values. Nevertheless, a recent assessment by the European Environment Agency (EEA, 2010) found that emission of NO\textsubscript{x} are 40 % lower, and those of PM\textsubscript{2.5} are 60% lower, than the amounts that would have been emitted by the road transport sector had Euro standards not been introduced.

Similar issues also arise for fuel consumption and tailpipe CO\textsubscript{2} emissions in relation to existing type approval test cycles for light duty vehicles. It has been known for some time that existing test cycles underestimate performance compared to real world application.

In order to address the issues with existing test procedures, work is currently underway on the Worldwide harmonized Light-duty Test Procedures (WLTP). This activity under the UNECE-GRPE aims to establish a worldwide test procedure to measure light duty vehicle emissions and energy consumption. However, the procedure is some years away from being fully developed and implemented, with further time also needed to adapt existing legislation to the new procedures (TNO et al, 2011). In Europe work is being carried out for the European Commission that aims to develop whole vehicle test cycles for a series of different duty cycles in order to facilitate the development of future regulation of GHG from HDVs (AEA, 2011).

Therefore, in the shorter term at least, until legislation based on real-world test cycles is in place the air-pollutant co-benefits of many low-carbon technologies is likely to be significantly greater than simple comparisons with Euro emission standards and fleet penetration rates for conventional vehicles might suggest. At the moment there are no plans under discussion for possible Euro 7/ VII standards for light/heavy duty vehicles respectively, although if these were developed it might be anticipated they might incorporate such real-world cycles.
2.3 Potential impacts of GHG reduction options on air pollutant emissions from transport

The main focus of this study is on passenger cars, as there tends to be more data available for this mode, and the technology for alternative powertrains is more advanced. Similar impacts would also be expected for the other road transport modes. This section considers the air pollutant emissions from low carbon passenger cars including:

1) Emissions from low carbon vehicles:
   a) Hydrogen vehicles;
   b) Battery electric vehicles;
   c) Hybrid vehicles.
2) Emissions from biofuels:
   a) Ethanol blends in petrol vehicles;
   b) Biodiesel blends in diesel vehicles.
3) Measures affecting driving profiles;
4) Non-technical measures; and
5) Non-exhaust air pollutant emissions.

Although the tailpipe emissions of many low carbon road transport options are low, some insight is necessary into the emissions over the fuel lifecycle (i.e. well-to-wheel, WTW). For example, indirect emissions occur in the production of electricity and hydrogen. Biofuels can cause increases or decreases in WTW emissions depending on the fuel specifications and particular fuel production pathway. Measures affecting driving profiles are known to have an impact on emissions, for example, driving style training and traffic management. Non-technical measures such as economic instruments and spatial policy may also affect air quality through impacts on transport activity and modal split. Finally, non-exhaust emissions are also considered, particularly those relating to tyre and brake wear.

In this section, we provide comparisons between the total lifecycle emissions of a range of air pollutants. Quantification of emissions at the national level is relevant for National Emission Ceilings (NEC). Although the absolute emissions are informative, they do not reveal distributional impacts. For example, the same amount of NO\textsubscript{x} may cause more damage if released in an urban environment as opposed to at a rural power station, because there are a greater number of people to affect. Even within cities, exposure varies depending on how long certain groups stay in polluted areas and what activities they engage in. For most pollutants, concentrations near busy roads are at least double the level found at background measurement sites (WHO, 2011). Drivers, cyclists and pedestrians are all affected, but it is difficult to separate the impacts of transport-related pollution from other sources.

The external costs of transport pollution, of which health impacts are by far the most important, have been summarised in the IMPACT study (CE Delft, 2008). EU-25 costs per tonne of pollutant are given as €4,400 for NO\textsubscript{x}, €1,000 for non-methane HCs, €5,600 for SO\textsubscript{2} and €26,000 for PM\textsubscript{2.5} (exhaust emissions outside built-up areas). Factors for PM\textsubscript{2.5} exhaust emissions in urban areas are substantially higher but vary depending on the location; for example, the highest factor given in €671,500 for emissions in urban metropolitan areas in Luxembourg. These are presented in Table 2.2, together with estimates for EU-25 based on the 2010 emissions of exhaust and non-exhaust PM from the TREMOVE model. Factors for non-exhaust PM\textsubscript{10} are lower than for exhaust PM\textsubscript{2.5}, but still significantly higher than for other air pollutants. Thus, for particulate emissions, the location of the emission-releasing activity is very important, as the impacts are much higher in densely populated urban areas. PM emissions also have a highly localised impact as they are not transported such significant distances in the atmosphere from their point of emission compared to other pollutants.
Table 2.2: Summary of air pollution cost factors based on those reported in the IMPACT study (CE Delft, 2008).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>NO₂</th>
<th>NMVOC</th>
<th>SO₂</th>
<th>PM₂₅ (exhaust)</th>
<th>PM₁₀ (non-exhaust – wear &amp; tear of brakes and tyres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local environment</td>
<td>N/A</td>
<td>N/A</td>
<td>Urban Metropolitan(¹)</td>
<td>Urban metropolitan(¹)</td>
</tr>
<tr>
<td>Austria</td>
<td>8,700</td>
<td>1,700</td>
<td>8,300</td>
<td>415,000</td>
<td>134,300</td>
</tr>
<tr>
<td>Belgium</td>
<td>5,200</td>
<td>2,500</td>
<td>11,000</td>
<td>422,200</td>
<td>136,200</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>1,800</td>
<td>200</td>
<td>1,000</td>
<td>43,000</td>
<td>13,800</td>
</tr>
<tr>
<td>Cyprus</td>
<td>500</td>
<td>300</td>
<td>2,000</td>
<td>243,700</td>
<td>78,700</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>7300</td>
<td>1000</td>
<td>8,000</td>
<td>252,600</td>
<td>81,400</td>
</tr>
<tr>
<td>Denmark</td>
<td>4,400</td>
<td>700</td>
<td>5,200</td>
<td>386,800</td>
<td>124,700</td>
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<td>800</td>
<td>100</td>
<td>1,800</td>
<td>133,400</td>
<td>43,400</td>
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<td>8,000</td>
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<td>245,400</td>
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<td>13,000</td>
<td>422,500</td>
<td>136,400</td>
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<td>174,500</td>
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<td>6,200</td>
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<td>400</td>
<td>4,300</td>
<td>299,600</td>
<td>96,400</td>
</tr>
<tr>
<td>Sweden</td>
<td>2,200</td>
<td>300</td>
<td>2,800</td>
<td>352,600</td>
<td>113,400</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>3,900</td>
<td>1,100</td>
<td>6,600</td>
<td>389,100</td>
<td>125,300</td>
</tr>
<tr>
<td><strong>EU-25</strong></td>
<td><strong>4,400</strong></td>
<td><strong>1,000</strong></td>
<td><strong>5,600</strong></td>
<td><strong>327,900</strong></td>
<td><strong>117,741</strong></td>
</tr>
</tbody>
</table>

Notes: (1) Cities > 0.5 million inhabitants; (2) Smaller and midsized cities < 0.5 million inhabitants; (3) AEA estimate based on 2010 PM emissions from the TREMOVE model.
Some studies estimate that the urban external cost of PM is as much as 20 times higher than the extra-urban cost (Chernyavsk & Gulli, 2008). Other impacts from air pollutants, such as acidification, exhibit their effects over a much wider area. A detailed assessment of proximity-related damage functions has not been possible within the time and resources of this study. As such, we quantify the total lifecycle emissions, and comment qualitatively on the distributional impacts. Further research needs to be conducted to calculate the net effects on health in detail.

The air pollutant emissions from transport considered in this chapter are therefore those with the highest external costs, which have also received the most attention in regulation and have proved the most difficult/costly to reduce, namely:

- NO\(_x\)
- SO\(_x\)
- PM

A detailed analysis of other types of air pollutant was not possible within the time and resources of this study. In addition, we focus on the near-term effects, as emissions from all types of vehicles will decrease over the longer term. Vehicle emissions will fall under the increasingly stringent Euro Standards. Upstream emissions from power plants will be reduced in compliance with the Large Combustion Plant Directive, the Industrial Emissions Directive, and the Renewable Energy Directive (see Section 2.4.2 for a more detailed discussion of policy implications). Any long term sustainable transport solution should have near-zero air pollutant emissions.

### 2.4 Low-carbon vehicles and air pollutant emissions

This section summarises the available information on the impact of low-carbon vehicles on air pollutant emissions. The summary focuses on passenger cars as:

1. The technology for alternative fuels (electricity, hydrogen and biofuels) is more advanced and is likely to penetrate the passenger car market before other modes;
2. Emissions from passenger cars have been the subject of greatest policy attention, whereas legislation for other vehicles tends to be less well-developed, therefore more information is available for cars;
3. Most of the supporting literature is limited to studies of passenger vehicles;
4. The impacts for other road transport modes are expected to be broadly similar for equivalent low carbon vehicle options.

Improvements to local air quality are a widely cited advantage of using electric- or hydrogen-powered vehicles. Electric and hydrogen fuel cell vehicles, with their zero tailpipe emissions, are particularly beneficial in sensitive areas such as city centres. Hydrogen internal combustion engines (ICE) emit only water vapour and smaller amounts of NO\(_x\), compared to other ICE vehicles. However, there may be a trade-off between lower emissions during vehicle use against higher emissions in the upstream phase.

Evaluating the overall emissions requires the complete fuel cycle (well-to-wheels) to be taken into account. The most comprehensive well-to-wheels (WTW) study in the European context was carried out by EUCAR, CONCAWE and the JRC (2007), which calculated energy and GHG emissions from a wide range of alternative fuels and powertrains. It did not, however, include non-GHG pollutants. A small number of studies which do include non-GHG pollutants have been carried out but the majority of these relate to areas outside of Europe. For example, Wang (2008) analyses the impact of alternative vehicle/fuel systems with respect to human health effects resulting from air pollution in the US. Studies which focus on non-European regions are not directly comparable to Europe because site-specific factors which affect the results vary significantly. These factors include vehicle size, electricity mix,
2.4.1 Hydrogen vehicles

Summary of Main Findings

⇒ Hydrogen can be produced from several processes and feedstocks. Currently, the main sources of hydrogen are natural gas reforming and coal gasification. Other potential processes include nuclear thermocracking, water electrolysis, biomass gasification, thermolysis and thermo-chemical cycles.

⇒ No European data were found which quantified the air pollutant emissions from different hydrogen production processes.

⇒ On a lifecycle basis (including fuel production and vehicle construction):
  o Hydrogen fuel cell vehicles emit lower levels of NO\textsubscript{x} compared to petrol internal combustion engine (ICE) vehicles.
  o Emissions of SO\textsubscript{x} are broadly comparable between hydrogen and ICE vehicles for most production processes, with hydrogen lifecycle emissions found to be only slightly higher on average.
  o Using hydrogen produced from water electrolysis causes the highest NO\textsubscript{x} and SO\textsubscript{x} emissions. This impact is likely to decrease in the future as renewable make a greater contribution to electricity generation.

⇒ On a well-to-wheels (WTW) basis (i.e. including fuel production and distribution only):
  o Hydrogen fuel cell vehicles significantly lower levels of NO\textsubscript{x} compared to gasoline and diesel ICES (75% and 85% reductions respectively for Euro 5 standards).
  o Hydrogen fuel cell vehicles significantly lower levels of SO\textsubscript{x} compared to gasoline and diesel ICES (61% and 53% reductions respectively for Euro 5 standards).
  o Hydrogen fuel cell vehicles (using hydrogen produced from steam reforming) significantly lower levels of PM compared to gasoline and diesel ICES. One study found lifecycle reductions of PM emissions by 72% and 79% respectively over diesel and gasoline Euro 5 standards.
  o Hydrogen fuel cell vehicles using hydrogen produced by water electrolysis may increase overall levels of PM from the fuel cycle in the short term.
  o However, tailpipe emissions of PM from hydrogen vehicles are zero. The impacts of PM emissions are much higher in densely populated urban areas, so hydrogen vehicles are likely to have a beneficial effect on health overall.

Hydrogen can be produced using a variety of feedstocks and processes, each with different implications for fuel cycle emissions. It can be used as a transport fuel in internal combustion engines (ICE) and fuel cell vehicles (FCV), the latter being more popular option because of their greater efficiency. Fuel cell vehicles have an operational efficiency of over 50%; more than twice that of a typical ICE (IEA, 2010a). Both types of vehicle face barriers from hydrogen storage issues and a lack of refuelling infrastructure.

Hydrogen is seen as a clean fuel, as tailpipe emissions are negligible. Overall lifecycle emissions are significantly affected by both the hydrogen production pathway and the vehicle combustion technology. The majority of hydrogen today is produced from fossil fuels – natural gas reforming and coal gasification (IEA, 2010a). Electrolysis of water and gasification of heavy fuel oils are also common. Other processes using renewable energy are being researched: Photoelectrolysis converts sunlight into hydrogen; Photobiological processes rely on organisms that produce hydrogen as a metabolic waste; Thermochemical processes decompose water at high temperatures using heat from nuclear or solar energy (EC, 2006). It is anticipated that in the long term hydrogen would be produced exclusively from renewable/low carbon sources (primarily from electrolysis of water).
Vehicle lifecycle analysis

Emissions from vehicles using hydrogen from various production processes are shown in Figure 2.5 for NO<sub>x</sub> and Figure 2.6 for SO<sub>x</sub>. Both figures show that lower emissions during operation may in fact be counteracted by higher emissions during fuel production.

Figure 2.5 demonstrates that in-use NO<sub>x</sub> emissions from hydrogen fuel cell vehicles are negligible. On a fuel lifecycle basis, hydrogen fuel cell vehicles emit less NO<sub>x</sub> than conventional vehicles. Overall, the most polluting hydrogen production method in terms of NO<sub>x</sub> emissions is water electrolysis (assuming a typical EU grid mix), and the least polluting is nuclear thermocracking. The NO<sub>x</sub> emissions from hydrogen burned in an internal combustion engine (ICE) are similar to those from gasoline, natural gas or LPG ICEs.

Figure 2.5: NO<sub>x</sub> life cycle emissions, passenger cars

Source: Chernyavska & Gulli (2008)
Notes: Upstream phase includes stages from fuel production to fuel distribution and storage as well as emissions from vehicles’ material and assembly. Vehicle operation is assumed to be 55% city driving and 45% highway driving. Electricity emissions assume the European average mix. Data for diesel NO<sub>x</sub> has not been included, as the study appears to have produced anomalous results. FC = fuel cell, ICE = internal combustion engine.

Figure 2.6 shows that fuel cycle emissions of SO<sub>x</sub> for hydrogen and conventional fuels are broadly comparable, with hydrogen vehicles showing only slightly higher emissions on average compared to ICEs. The clear exception of hydrogen production from water electrolysis, which emits 0.90 gSO<sub>x</sub>/km; the next highest is a gasoline ICE at 0.34 gSO<sub>x</sub>/km. Water electrolysis is assumed to use electricity based on the European average electricity mix; this will vary with time. A detailed discussion of the electricity generation mix is provided in Section 2.4.2. In-use SO<sub>x</sub> emissions from conventional fuel-burning vehicles are low because the sulphur content of fuels is regulated. The mandatory limit for petrol and diesel was set at 50ppm in 2005, reducing to <10ppm in 2009 (Directive 2003/17/EC).
Although hydrogen technology show clear and consistent reductions in NO\textsubscript{x} and SO\textsubscript{x} during operation when compared to both petrol and diesel ICE vehicles, the benefits over a lifecycle basis are not as clear. Table 2.3 summarises the comparative emissions for fuel cell vehicles compared to fossil fuel ICE vehicles.

Table 2.3: Summary of NO\textsubscript{x} and SO\textsubscript{x} emissions of hydrogen vehicles compared to fossil fuel ICE on a lifecycle basis

<table>
<thead>
<tr>
<th>Production method</th>
<th>Compared to petrol ICE</th>
<th>Compared to diesel ICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO\textsubscript{x}</td>
<td>SO\textsubscript{x}</td>
</tr>
<tr>
<td>Natural gas reforming</td>
<td>▼</td>
<td>=</td>
</tr>
<tr>
<td>Water electrolysis</td>
<td>▼</td>
<td>▲</td>
</tr>
<tr>
<td>Coal gasification</td>
<td>▼</td>
<td>=</td>
</tr>
<tr>
<td>Nuclear thermocracking</td>
<td>▼</td>
<td>=</td>
</tr>
</tbody>
</table>

Source: Adapted from Chernyavsk & Gulli (2008)

Notes: ▲ emissions have increased compared to ICE by more than 0.1g/km; ▼ emissions have decreased compared to ICE by more than 0.1g/km; = lifecycle emissions are within 0.1g/km of each other; data for diesel NO\textsubscript{x} has not been included, as the study appears to have produced anomalous results.

Hydrogen fuel cell vehicles emit lower levels of NO\textsubscript{x} on a lifecycle basis regardless of the production method used when compared to petrol ICEs. A comparison between hydrogen vehicles and diesel ICEs was not possible using the data in this study, but the benefits are likely to be even greater than for the comparison with petrol ICEs. This is because the tailpipe emissions from diesel ICEs are much greater, e.g. 0.18 g NO\textsubscript{x}/km for Euro 5 diesel engines compared to 0.06 g NO\textsubscript{x}/km for Euro 5 petrol engines and negligible emissions from...
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

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Commercial
Ref. AEA/ED56293/Task 1 Paper Draft – Issue No. 2

hydrogen vehicles. Although hydrogen FCV have zero tailpipe emissions of NO\textsubscript{x}, including the upstream processes means that emissions are between 0.155 and 0.388 g NO\textsubscript{x}/km.

The differences when considering SO\textsubscript{x} emissions from petrol and diesel ICEs compared to hydrogen vehicles are not so clear. Using hydrogen produced from water electrolysis may actually lead to an increase in lifecycle emissions in the near-term, assuming the European average electricity mix is used (0.902 g SO\textsubscript{x}/km). Other hydrogen production methods cause much lower levels of SO\textsubscript{x} in the upstream phase (between 0.265 and 0.295 g SO\textsubscript{x}/km). Again, tailpipe emissions of SO\textsubscript{x} are zero for hydrogen fuel cell vehicles, but they are also very low for all other vehicle types, ranging from 0.009 to 0.021 g SO\textsubscript{x}/km. In the medium to longer term, emissions of air pollutants from electricity generation are in concert likely to fall very significantly. This is due to a combination of greater regulation and control of air quality pollutants from conventional power stations, as well as an increasing proportion of renewable and other low carbon electricity generation options utilised to reduce GHG emissions.

**Energy well-to-wheels analysis**

On a well-to-wheels basis, hydrogen fuel cell vehicles (using hydrogen centrally produced from steam reforming) have significant advantages over ICEs in terms of both upstream and tailpipe emissions of NO\textsubscript{x} and SO\textsubscript{x} (Torchio, 2010). The results in Figure 2.7 are specific to Euro 5 standards (<0.06 gNO\textsubscript{x}/km for petrol cars and <0.18 gNO\textsubscript{x}/km for diesel cars as of 2009), although clearly the advantage of hydrogen fuel cell vehicles will be maintained under Euro 6 standards (NO\textsubscript{x} unchanged for petrol cars, but reducing to 0.08 gNO\textsubscript{x}/km for diesel cars as of 2016). Note that the results are different to Chemyavsk & Gulli (2008) because emissions from vehicle materials and assembly are not included. Well-to-tank (WTT) energy includes extraction, chemical processing and transport; Tank-to-wheels (TTW) emissions are the tailpipe emissions.

**Figure 2.7: NO\textsubscript{x} and SO\textsubscript{x} emissions from ICEs and hydrogen fuel cell car (Euro 5/6 standard saloon)**

Source: Torchio (2010)

Notes: The car under consideration is a typical European 5-seater saloon (curb weight of 1181kg), conforming to Euro 5 standard and tested using the European NEDC cycle. The fuel sulphur limits conform to the European limit of 10mg/kg that has been in place since January 2009. Natural gas used in hydrogen production is assumed to be transported through pipelines for an average of 4,000km and produced in large central plants. The fuel cell vehicle uses proton exchange membrane technology and is fed by hydrogen from an onboard tank.

WTT emissions of NO\textsubscript{x} from hydrogen fuel cell vehicles are reduced by 57% compared to gasoline ICEs and by 47% compared to diesel ICEs. Total Well-to-wheels emissions are reduced by 75% and 86% compared to gasoline and diesel ICEs respectively.
WTT emissions of SO$_x$ from hydrogen fuel cell vehicles are reduced by 61% compared to gasoline ICEs and by 53% compared to diesel ICEs. Total Well-to-wheels emissions are reduced by a similar percentages because TTW emissions of SO$_x$ are very small due to the 10mg/kg sulphur limit for fuels introduced in 2009. Torchio (2010) could not find any European data for well-to-tank air pollutant emissions for hydrogen pathways. Therefore, the values are estimated by assuming emissions due to extraction and transport of natural gas are equal to the CNG 4000km pathway; the emissions from stream reformation are given assuming according to the average EU power plant.

Torchio (2010) also compares PM emissions between hydrogen and conventionally fuelled ICE cars. Hydrogen fuel cell cars show significant benefits in this study, reducing PM emissions by 72% and 79% respectively over diesel and gasoline ICEs. In addition to lowering PM emissions overall, the emissions are also moved entirely upstream where the external costs are likely to be much lower as production facilities will be located away from urban areas.

Figure 2.8: PM emissions from ICEs and hydrogen fuel cell cars (Euro 5/6 standard saloon)

Source: Torchio (2010)

Notes: The car under consideration is a typical European 5-seater saloon (curb weight of 1181kg), conforming to Euro 5 standard and tested using the European NEDC cycle. The fuel sulphur limits conform to the European limit of 10mg/kg that has been in place since January 2009. Natural gas used in hydrogen production is assumed to be transported through pipelines for an average of 4,000km and produced in large central plants. The fuel cell vehicle uses proton exchange membrane technology and is fed by hydrogen from an onboard tank.

Wang (2001) finds that, in the US, hydrogen fuel cell electric vehicles (hydrogen produced from reformed natural gas) emit 34% less NO$_x$, 28% less SO$_x$ and 33% less PM$_{10}$ compared to an ICE. The same study finds that using hydrogen from water electrolysis in a hydrogen fuel cell electric vehicles could cause 320% more NO$_x$, 800% more SO$_x$ and 136% more PM$_{10}$ compared to an ICE, assuming the average US grid mix (which utilises a much higher proportion of coal in its generation mix versus the EU). This highlights the importance of considering the fuel production pathway.
2.4.2 Pure electric vehicles

**Summary of Main Findings**

- Due to their zero tailpipe emissions, lifecycle emissions of pollutants from EVs are entirely dependent on the mix of fuels and generation technologies used to produce the electricity that powers them.
- There can be huge variations in the upstream emissions due to the many possible combinations of input fuel, production process and scrubbing technology.
- Future emissions will decline in step with the introduction of newer and cleaner plants and with the greater contribution from renewable generation technologies. Significant European legislation driving change in this area includes the Large Combustion Plant Directive; the Industrial Emissions Directive; the Renewable Energy Directive.
- Emissions of NO\textsubscript{x}, SO\textsubscript{2} and PM are virtually eliminated by switching to renewable energy sources such as wind, hydropower or nuclear.
- Generation from coal and oil shows the highest overall emissions of NO\textsubscript{x}, SO\textsubscript{2} and PM. However, newer technologies such as combined cycle plants and pressurised water reactors reduce emissions significantly when generating electricity from coal and oil.
- Emissions of NO\textsubscript{x}, SO\textsubscript{2} and PM are increased if the electric vehicle is assumed to be powered from electricity produced using the typical generation mix today, due to the high contribution of coal-based power plants.
- Emissions of NO\textsubscript{x} and SO\textsubscript{2} are decreased if the electric vehicle is assumed to be powered from marginal generation technologies. That is, assuming the extra production capacity required to meet additional electricity demand is met using combined cycle gas turbine plants; these plants are newer, cleaner and more efficient than the stock average.
- Increased uptake of electric vehicles (including battery electric, plug-in and range extended types) is expected to lead to higher emissions of overall NO\textsubscript{x} (well-to-wheel). Estimates range from 50 – 250kton in 2030 depending on the level of uptake.
- Increased uptake of electric vehicles (including battery electric, plug-in and range extended types) is expected to lead to lower emissions of overall PM, as additional emissions from the power sector are small compared to the reduction of direct exhaust emissions.

Electric Vehicles (EVs) have no tailpipe emissions; therefore they have positive implications for air pollutant emissions at the point of use. EVs are particularly beneficial where air quality concerns are important and trip distances are short, for example in cities and sensitive areas such as warehouses. In addition, EVs provide competitive operating costs; high acceleration (at least at lower speeds - depends on specifications at higher speeds); lower maintenance costs due to fewer moving parts; and fuel economy improvements of 60-70% (IEA, 2010a).

Charging cars in off-peak periods (e.g. overnight) can help improve electricity generation efficiency by flattening out the demand profile (Arup, 2008). However, EVs which operate entirely from on-board batteries currently have a reduced range compared to conventional vehicles (up to 100km). The quiet operation of EVs has been a cause for concern and therefore regulations on minimum noise levels are in development.

Production of electricity for use by EVs leads to emissions of air pollutants upstream at power station stations. Air quality impacts therefore are dependent on the electricity generation mix. Overall emissions of NO\textsubscript{x} and SO\textsubscript{2} may be increased if power sector emissions are included, particularly if coal is the source fuel (Arup, 2008). These impacts are likely to reduce over time; however electricity-generating power plants generally have long operational lifetimes exceeding 50 years. Emission reductions will be stimulated by legislation including:

- Large Combustion Plant Directive (LCPD 2001/80/EC);
- Industrial Emissions Directive (2010/75/EU); and
The Large Combustion Plant Directive regulates acidifying pollutants, particles and ozone precursors. Under the LCPD, existing combustion plants have the option to either install abatement technology (e.g. flue gas desulphurisation) or opt out (leading to restricted operation post-2007 and closure in 2015). The Industrial Emissions Directive came into force on 6 January 2011 and requires power plants to apply best available technologies that optimise their environmental performance. The Directive will apply strict limits on air pollution and lays down rules on the integrated prevention and control of pollutants such as NO$_x$, SO$_2$ and dust. Installations will have until 2016 to comply. Finally, the Renewable Energy Directive calls for 20% of overall energy in Europe to be supplied by renewable sources.

The emissions intensity of SO$_2$ and NO$_x$ from conventional power plants in Europe has decreased substantially in the past decades. This is mainly due to decreased coal use, replacement of old coal plant and the uptake of abatement technologies. Combustion modification (e.g. low NO$_x$ burners) and flue-gas treatment (e.g. selective catalytic reduction) can be used to reduce emissions.

Figure 2.9: Emissions intensity of public conventional thermal power production, EEA-32

Source: EEA (2010)
Notes: Includes power production of electricity and heat
Vehicle lifecycle analysis

In the UK, research for the Department for Transport (Arup, 2008) included a comparison of the lifecycle air acidification emissions of EVs. This includes emissions from power generation, as well as vehicle production and disposal. The findings are presented in Figure 2.10. Air acidification gases include sulphur oxides, nitrogen oxides and ammonia, expressed here as SO₂-equivalent. The lifecycle emissions (taken over a vehicle life of 180,000km) are shown for conventional petrol and diesel engines. Two sets of EV impacts are shown: the first assumes that electricity is drawn from the UK National Grid, using the average generation mix. The second assumes that marginal electricity to power EVs is produced using Combined Cycle Gas Turbine (CCGT) plant.

Figure 2.10: Lifecycle emissions of acidifying pollutants for different vehicle types (kg SO₂-equivalent)

![Figure 2.10: Lifecycle emissions of acidifying pollutants for different vehicle types (kg SO₂-equivalent)](image)

Source: Arup (2008)
Notes: SO₂-equivalent emissions include sulphur oxides (SOx), nitrogen oxides (NOx) and ammonia (NH₃). Impact of EVs includes fuel extraction, transport and combustion at power stations; vehicle life is taken to be 180,000km; the EV has a 35kWh battery. The EV is assumed to have an efficiency of 0.16kWh/km in 2010, 0.13kWh/km in 2020 and 0.11kWh/km in 2030. The ICE is assumed to have an efficiency of 0.06l/km in 2010, 0.05l/km in 2020 and 0.042l/km in 2030.

In 2010, SO₂-equivalent emissions are substantially higher for EVs using the typical UK grid mix when considered on a lifecycle basis. This is because much generation relies on fossil fuel combustion. Although lifecycle emissions are higher, there are no tailpipe emissions from EVs, which would improve air quality in urban environments. The impact of EVs falls in 2020 and 2030, due to the greater contribution of nuclear and renewables. The impact of petrol and diesel vehicles falls as the ICE technology improves. The impact of petrol and diesel cars is partly from tailpipe emissions (35% and 69% respectively) and partly from emissions during extraction, refining and transportation of fuel. Electricity produced using Combined Cycle Gas Turbines (CCGT) could be considered as the marginal source – i.e. the additional electricity capacity that is needed to fuel increased numbers of EVs is supplied using new CCGT capacity. If this is the case, then lifecycle emissions from EVs are much lower than for petrol and diesel cars. Over time, it is clear that the difference between EVs and ICEs becomes less pronounced as the electricity mix changes and engine technology improves.
Energy well-to-wheel analysis

A study by Torchio (2010) found that EVs emit higher levels of NO\(_x\) and SO\(_x\) on a WTW basis compared to Euro 6 standard vehicles. Emissions from EVs using the average EU grid mix are 36% higher compared to petrol ICES, and 19% higher compared to diesel ICES. For SO\(_2\), emissions are increased by 249% compared to petrol ICES, and 332% compared to diesel ICES. The only case in which EVs show an improvement is compared to Euro 5 Diesel ICES for NO\(_x\) emissions (22% lower). Note that the results are different to Arup (2008) because emissions from vehicle materials and assembly are not included. Well-to-tank (WTT) energy includes extraction, chemical processing and transport; Tank-to-wheels (TTW) emissions are the tailpipe emissions.

Figure 2.11: NO\(_x\) (left) and SO\(_x\) (right) emissions from ICES and EVs (Euro 5/6 standard saloon)

Source: Torchio (2010)
Notes: The car under consideration is a typical European 5-seater saloon (curb weight of 1181kg), conforming to Euro 5 standard and tested using the European NEDC cycle. The fuel sulphur limits conform to the European limit of 10mg/kg that has been in place since January 2009. The EU power mix is assumed to be 27% nuclear, 28% solid, 25% gas, 2% oil and 18% renewables. Euro 6 standards have been added by the study team, assuming WTT emissions remain the same.

Torchio (2010) also found that an electric car emitted higher levels of PM compared to its diesel and petrol ICE counterparts over the whole lifecycle. Total emissions of PM from BEVs using the average EU grid mix are 1% higher compared to petrol ICES, and 31% higher compared to diesel ICES. However, tailpipe emissions from electric vehicles are zero, which is important since the impacts of PM are highly location-dependent. Upstream emissions at the power generation plant are unlikely to be located close to densely populated urban areas, where the most damage from PM is caused. The overall impact of PM emissions from BEVs is likely to be significantly smaller than for conventional vehicles therefore.
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

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Figure 2.12: PM emissions from ICEs and EVs (Euro 5/6 standard saloon)

Source: Torchio (2010)
Notes: The car under consideration is a typical European 5-seater saloon (curb weight of 1181kg), conforming to Euro 5 standard and tested using the European NEDC cycle. The fuel sulphur limits conform to the European limit of 10mg/kg that has been in place since January 2009. The EU power mix is assumed to be 27% nuclear, 28% solid, 25% gas, 2% oil and 18% renewables. Euro 6 standards have been added by the study team, assuming WTT emissions remain the same.

It should be emphasised that although EVs currently emit significant levels of NO_x, SO_2 and PM upstream at power stations, this effect is likely to diminish with the changing generation mix. In general, most European countries have a diverse portfolio, although the generation mix varies. For example, France currently relies heavily on nuclear power (77%) and Poland on coal (91%). Some countries have political or social objections to nuclear power and hence have no electricity from this source.

Figure 2.13: Average EU-27 electricity generation mix (2007)


According to the World Energy Outlook (IEA, 2009), generation from gas-fired plants in Europe is expected to increasingly replace coal until 2025, before dropping again. Generation from CCS plants gradually increases to 6% of total generation in 2030.
Figure 2.14: European electricity generation by type.

Source: IEA (2009)

Notes: The reference scenario predicts how electricity generation would evolve if there were no changes to existing policies and measures. The 450 scenario considers how markets might change if countries acted to restrict the global temperature increase to 2°C. OECD+ countries are assumed to take on national emission-reduction commitments for 2020.

The IEA’s 450 scenario predicts how markets might change if countries take strong action to keep global temperature increases below 2°C. In this scenario, coal generation is reduced to near-zero by 2030; nuclear generation remains constant and wind power grows to 20% of total generation by 2030. Other renewables also see a significant increase.

Figure 2.15: European Union power generation capacity in the 450 Scenario

Source: IEA (2009)

Notably, the European Commission’s Transport White Paper (EC, 2011) assumes that the GHG intensity from electricity generation will fall in line with the “Effective and widely accepted technology” technology scenario from the Roadmap to a Low Carbon Economy by 2050. The three main low carbon technologies in the power generation sector are renewables, nuclear and CCS-equipped fossil fuel plants. Near complete decarbonisation is achieved using these three technologies, which together increase their share in total electricity production from 45% in 2005 to around 78% in 2030, to nearly 100% in 2050. Reducing GHG emissions will also reduce emissions of air pollutants as it entails a shift to more renewable energy sources.
Figure 2.16 shows upstream emissions from power production systems in Europe. This includes full lifecycle effects from all stages including resource extraction, processing, production of infrastructure and fuels, transport, conversion efficiency and waste management. Direct power plant emissions will be affected by the installation and efficiency of any emission control technologies.

**Figure 2.16: Cumulative SO$_2$ and NO$_x$ emissions for current and new technologies for power production systems**

![Graph showing emissions from various power production technologies](image-url)

- **Source:** ExternE-Pol (2005)
- **Notes:** PWR = pressurised water reactor; PFBC = pressurized fluid bed combustion; photovoltaic figures assume installations are located in Southern Europe.
Figure 2.17: Cumulative PM$_{2.5}$ emissions for current and new technologies for power production systems

It can be seen that emissions of NO$_x$, SO$_2$ and PM$_{2.5}$ are virtually eliminated by switching to wind, hydropower or nuclear. They are highest in regions served by conventional coal or oil power plants. Newer fossil fuel technologies such as combined cycle plants and pressurised water reactors reduce emissions significantly for oil and coal. For illustrative comparison, if we assume an EV consumes 0.16kWh/km (after Arup, 2008), its indirect NO$_x$ emissions would range from 0.01gNO$_x$/km to 0.45gNO$_x$/km depending on the electricity source. In this case, indirect emissions from EVs would be lower than the Euro 6 tailpipe limit for new petrol/diesel passenger cars (0.08g/km from 2014) for all non-fossil fuel sources of electricity. If well-to-tank emissions from petrol and diesel are also taken into account, EVs offer an even greater advantage. A similar analysis yields estimates of 0.01gSO$_2$/km to 1.11gSO$_2$/km and 0gPM$_{2.5}$/km – 0.08gPM$_{2.5}$/km for an EV using 0.16kWh/km.
A dramatic increase in market share of EVs will result in surging electricity demand. CE Delft (2011) has analysed the potential effect this could have under three scenarios and a Reference Case based on TREMOVE version 3.3. The results include penetration of both pure/fully electric vehicles (FEVs) and plug-in hybrid electric vehicles (PHEVs) and extended range electric vehicles (EREVs) – see Section 2.4.3 for more discussion of PHEVs and EREVs.

<table>
<thead>
<tr>
<th>Table 2.4: EU-27 car fleet (million cars)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference</strong></td>
</tr>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>Scenario 1</td>
</tr>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>PHEV</td>
</tr>
<tr>
<td>EREV</td>
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<tr>
<td>FEV</td>
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<tr>
<td>Scenario 2</td>
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<tr>
<td>PHEV</td>
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<tr>
<td>EREV</td>
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<tr>
<td>FEV</td>
</tr>
<tr>
<td>Scenario 3</td>
</tr>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>PHEV</td>
</tr>
<tr>
<td>EREV</td>
</tr>
<tr>
<td>FEV</td>
</tr>
</tbody>
</table>

Source: CE Delft (2011)

In the years 2010-2020, the impact on fossil fuel use is negligible, but after 2020 they are gradually replaced by electricity.

**Figure 2.18: Development of electricity use in the EU (PJ/year)**

Source: CE Delft (2011)
The additional plant construction by 2030 is 18, 11 and 27 GW respectively under Scenarios 1, 2 and 3. This correlates with the different demand modelled in the three scenarios. Generally, the proportional increase in capacity across types is similar in all cases, where gas-fired generation is favoured. However, unmanaged EV charging requires greater flexibility within the system, and calls for larger peaking capacity from fossil fuel based plant. Smart charging infrastructure enables the greater use of wind generation to handle additional peak load requirements.

Further analysis by CE Delft on the air quality impacts notes that the effects depend on a number of factors. As a first estimate, the EU-average shares shown in Figure 2.18 are assumed to be evenly distributed across the EU, in which case no significant impacts on air quality are expected before 2025/2030. However, market uptake is likely to be concentrated in regions with favourable circumstances such as government incentives, therefore the benefits will be felt in these areas more. The impact will also depend on the share of these cars in total pollution. The developments of NO\textsubscript{x} and PM\textsubscript{10} emissions of passenger cars in the EU is shown in Figure 2.19 and Figure 2.20.

**Figure 2.19: Direct NO\textsubscript{x} exhaust emissions of passenger cars in the EU**

![Figure 2.19: Direct NO\textsubscript{x} exhaust emissions of passenger cars in the EU](image)

**Source:** CE Delft (2011)

**Figure 2.20: Direct PM\textsubscript{10} emissions of passenger cars in the EU (exhaust plus type/vehicle emissions)**

![Figure 2.20: Direct PM\textsubscript{10} emissions of passenger cars in the EU (exhaust plus type/vehicle emissions)](image)

**Source:** CE Delft (2011)
The analysis excludes upstream emissions (well-to-wheel) and shows only tank-to-wheel emissions. The reduction in emissions due to the tightening of regulations is clearly shown. Replacement of conventional cars with EVs further reduces these emissions by a maximum of 1% in 2020, and by 6 – 26% in 2030 depending on the EV market uptake.

The impacts of increased EV uptake on overall NO\textsubscript{x} emissions (well-to-wheel) is shown in Figure 2.21. In all scenarios, the additional NO\textsubscript{x} emissions from power production lead to an overall increase in NO\textsubscript{x} emissions. The net increase is around 50, 150 and 240 kton NO\textsubscript{x} in 2030 for each of the three scenarios. However, the wide range of scrubbing technologies and the different ways in which Member States regulate NO\textsubscript{x} emissions introduces uncertainties into the modelling of emissions from electricity production.

**Figure 2.21:** Overall impact on NO\textsubscript{x} emissions of passenger car transport in the EU – emissions from both vehicles and power production

Source: CE Delft (2011)

Notes: Emissions shown for well-to-wheel. Emissions from electricity include power production emissions only, and exclude emissions due to e.g. coal mining or gas production

In the case of PM\textsubscript{10} emissions, the additional increases from the power sector are relatively small compared to the reduction of direct vehicle emissions, therefore the uptake of EVs leads to a net reduction in PM\textsubscript{10} emissions.

**Figure 2.22:** Overall impact on PM\textsubscript{10} emissions of passenger car transport in the EU – emissions from both vehicles and power production
2.4.3 Hybrid and plug-in hybrid vehicles

**Summary of Main Findings**

- The air quality benefits of hybrid electric vehicles (HEVs) and plug-in hybrid vehicles (PHEVs) depend on the drive cycle. They are most beneficial when used in urban environments. There is little or no gain in efficiency compared to conventional internal combustion engines (ICEs) during highway driving.
- HEVs have improved NOx and SOx emissions compared to their conventional ICE counterparts.
- For HEVs compared to ICEs:
  - Total NOx emissions on a *lifecycle basis* are reduced by 26% for petrol engines
  - Total NOx emissions on a *well-to-wheels basis* are around 14% lower for petrol and diesel engines
  - Total SOx emissions on a *lifecycle basis* are reduced by around 23% per km for both petrol and diesel engines
  - Total SOx emissions on a *well-to-wheels basis* are around 18% lower per km for both petrol and diesel engines
- PHEVs show a fossil fuel displacement relative to *ICES* of 42% to 78% depending on their all-electric driving range.
- PHEVs show a fossil fuel displacement relative to *HEVs* of 12% to 66%.
- Fossil fuels are displaced with electrical energy; therefore the overall emission impact depends on the electricity grid mix.
- Evidence from the US suggests that PHEVs would reduce emissions of NOx and PM compared to ICEs, but could increase levels of SOx depending on the method of electricity generation.

Hybrid vehicles can use energy from multiple sources, of which at least one allows storage of surplus energy.

- **Conventional hybrid electric vehicles (HEVs):** HEVs are powered by a combination of a conventional fossil fuel engine and an electric motor with battery storage. The battery is charged by regenerative braking and excess energy from the ICE.
- **Plug-in hybrid electric vehicles (PHEV):** the battery is the main energy source, but a combustion engine running on hydrocarbons (potentially substitutable with a fuel cell in the long term) is used after batteries are depleted below a certain threshold. The vehicle operates as a regular hybrid at this point and the combustion engine can provide direct tractive power. The battery is charged primarily with electricity from the national grid (or independent external electricity generation source).
- **Extended-range electric vehicles (EREV):** the battery is the main energy source, but a smaller range-extender combustion engine is used to sustain the battery where distances exceed the electric range. The range-extending combustion engine does not provide direct tractive power, but rather acts purely as a generator. The battery is charged primarily with electricity from the national grid (or independent external electricity generation source).

As battery is charged by regenerative braking, hybrids are particularly beneficial in urban conditions which are characterised by frequent braking and accelerating. The increased use of regenerative braking is expected to reduce particulate emissions from brake wear – see Section 2.7 for more details on non-exhaust air pollutant emissions. For conventional hybrids, there is little or no gain in fuel efficiency relative to a conventional ICE when travelling at higher and steady speeds (King, 2007).
Vehicle lifecycle analysis

HEVs have improved NO\textsubscript{x} and SO\textsubscript{x} emissions on a lifecycle basis compared to their conventional internal combustion engine (ICE) counterparts (Chernyavska & Gulli, 2008). Petrol HEVs show a 26% improvement over petrol ICEs. For emissions of SO\textsubscript{x}, the major benefit arises from reduced upstream emissions due to improved fuel economy; HEVs have around 35% better fuel efficiency over the assumed vehicle operation (55% city driving and 45% highway driving). Although in-use air quality pollutant emissions are still reduced by a substantial percentage, the overall magnitude is smaller. Total SO\textsubscript{x} emissions from both diesel and petrol HEVs are around 23% lower than from their ICE equivalents.

Figure 2.23: NO\textsubscript{x} and SO\textsubscript{x} emissions of hybrid passenger cars compared to conventional ICES

Source: Chernyavska & Gulli (2008)

Notes: Upstream phase includes stages from fuel production to fuel distribution and storage as well as emissions from vehicles’ material and assembly. Vehicle operation is assumed to be 55% city driving and 45% highway driving. Data for diesel NO\textsubscript{x} has not been included, as the study appears to have produced anomalous results.

Energy well-to-wheel analysis

Comparing well-to-tank emissions also implies that HEVs will reduce total emissions of NO\textsubscript{x} and SO\textsubscript{x}. For both petrol and diesel engines, hybridised versions emit around 14\% less NO\textsubscript{x} and 18\% less SO\textsubscript{x} per km. These results are for a Euro 5 standard vehicle. Euro 6 standards will apply to passenger vehicles from 2014. The NO\textsubscript{x} emission limit for petrol vehicles will not change, but for diesel vehicles it will reduce from 0.18 gNO\textsubscript{x}/km to 0.08 gNO\textsubscript{x}/km.
Figure 2.24: NO\textsubscript{x} and SO\textsubscript{x} emissions from ICEs and HEVs

Source: Torchio (2010)
Notes: The car under consideration is a typical European 5-seater saloon (curb weight of 1181kg), conforming to Euro 5 standard and tested using the European NEDC cycle. The fuel sulphur limits conform to the European limit of 10mg/kg that has been in place since January 2009.

In terms of PM emissions, Torchio (2010) finds that hybrid versions reduce emissions from the fuel lifecycle by 17% compared to petrol vehicles and by 19% compared to diesel vehicles. Importantly the direct TTW emissions likely to be emitted in more densely populated areas are reduced by around 20% for both gasoline and diesel hybrid types.

Figure 2.25: PM emissions from ICEs and HEVs

Source: Torchio (2010)
Notes: The car under consideration is a typical European 5-seater saloon (curb weight of 1181kg), conforming to Euro 5 standard and tested using the European NEDC cycle. The fuel sulphur limits conform to the European limit of 10mg/kg that has been in place since January 2009.

Note that because HEVs do not use an external source of electrical energy (as opposed to PHEVs, which can plug into the grid), these savings are entirely due to improved engine combustion efficiency (with the ICE being utilised closer to its optimal power/operational band). The benefits of HEVs will increase with greater proportions of city driving, which is typically characterised by frequent braking and acceleration.

Plug in hybrid electrical vehicles (PHEVs) can be charged by plugging into the electrical grid. PHEVs operate as a mixture of HEVs and pure electric vehicles; thus, vehicle fossil fuel consumption can be displaced by electrical power, which means the emission impacts from
this part of the vehicle operation will be similar to those of pure battery electric vehicles (see Section 2.4.2). The fraction of total energy capacity remaining in the battery – the state of charge (SOC) – varies within a maximum and minimum. PHEVs have a technological advantage in that they can drive on different energy modes. Two basic modes are:

- Charge depleting – the vehicle is powered by the battery only. The battery’s SOC reduces to a minimum level. This mode can operate with the internal combustion engine turned on or off.
- Charge sustaining – the SOC remains, on average, at the same level, by recharging through regenerative braking. In this mode, PHEVs behave like conventional HEVs.

In pure-electric mode, the battery-only range is restricted to a given number miles by a controlled depth of discharge (usually 70-80%) in charge depletion mode. In charge sustaining HEV mode, the battery switches into cycles of repeated high power shallow discharge.

As a result, the two modes can be combined in a way that reaps the full benefits of PHEVs. Compared to battery-only vehicles (which use only electricity) and HEVs (which use only conventional fuels), the final energy consumption mix, and therefore the air quality impacts, for a PHEV is more complex to assess. The overall environmental impact of PHEVs depends on charging strategy, battery pack capacity, driving patterns and the type of engine (Peterson et al, 2011). Net emissions of NO\textsubscript{x} were generally reduced, but those for SO\textsubscript{2} could increase without additional investment in scrubbing technology by the electric power generation sector (see also Section 2.4.2).

PHEVs show measurable fuel savings compared to both conventional internal combustion engine (ICE) vehicles, and HEVs. The actual fuel displacement varies widely depending on the all-electric range of the PHEV, how often a vehicle is charged and the driving conditions. A summary of recent studies is shown in Figure 2.26 (Dowds et al, 2009). The fuel displacement rates range from 42% to 78% relative to ICEs and from 12% to 66% relative to HEVs. The notations PHEV\textsubscript{x} is used, where x indicates the all-electric range (miles) of the PHEV.

**Figure 2.26: Fuel displacement from PHEVs with varying all-electric range**

![Fuel displacement chart](image)

*Source: Dowds et al. (2009)*
The long-term energy performance of PHEVs has been assessed by EPRI (2007). This analysis splits the energy use between gasoline and electricity. In general, vehicles that are driven on many short trips with frequent recharging events will have a higher ratio of electricity to gasoline use.

### Table 2.5: Energy consumption of different vehicles in 2010 and 2050

<table>
<thead>
<tr>
<th>Energy consumption</th>
<th>ICE</th>
<th>HEV</th>
<th>PHEV10</th>
<th>PHEV20</th>
<th>PHEV40</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline (l)</td>
<td>1847</td>
<td>1198</td>
<td>1049</td>
<td>609</td>
<td>406</td>
</tr>
<tr>
<td>Electricity (kWh)</td>
<td>-</td>
<td>-</td>
<td>467</td>
<td>1840</td>
<td>2477</td>
</tr>
<tr>
<td>2050</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline (l)</td>
<td>1514</td>
<td>981</td>
<td>859</td>
<td>498</td>
<td>332</td>
</tr>
<tr>
<td>Electricity (kWh)</td>
<td>-</td>
<td>-</td>
<td>382</td>
<td>1504</td>
<td>2024</td>
</tr>
</tbody>
</table>

Source: EPRI (2007)

Notes: Assumes annual mileage of 12,000 miles; assumed fuel economy for ICE is 24.6mpg in 2010 and 30.0mpg in 2050; assumed fuel economy for other vehicle types is 37.9mpg in 2010 and 46.3mpg in 2050; assumed electric efficiency is 0.312kWh/mi in 2010 and 0.255 in 2050.

Studies from the US provide quantitative estimates for the impacts of HEVs and PHEVs on air pollutant emissions. Wang (2001) suggests that HEVs could reduce NOx by 25%, SOx by 29% and PM10 by 6% compared to ICEs. PHEVs using the US average grid mix (with a much higher proportion of coal than the EU) could reduce NOx by 2%, but increase SOx by 53% and increase PM10 by 2%. The Minnesota Pollution Control Agency (2007) looked at the effects if electricity was generated using 60% coal and 40% wind power. The study modelled emissions in 2020 for comparable mid-sized saloons. As a percentage of ICE emissions, HEVs would emit 80% of the NOx, 63% of the SOx and 76% of the PM2.5. A PHEV with a 20 mile all-electric range would emit 62% of the NOx, 170% of the SOx, and 71% of the PM2.5 of an ICE. A PHEV with a 60 mile all-electric range would emit 48% of the NOx, 265% of the SOx, and 66% of the PM2.5. In general, it was found that HEVs reduce emissions of all pollutants, and PHEVs generally reduce emissions of NOx and PM, but could increase emissions of SOx because of the high sulphur content of the coal used to generate electricity. However, with decarbonisation of the electricity generation mix this assessment would be expected to change significantly, with substantial benefits for PHEV over conventional vehicles for highly decarbonised electricity generation.

An important benefit of PHEVs is that when using the all-electric mode, all pollutants are shifted from the tailpipe to a small number of large power plants in less-populated areas. Therefore the net health impacts of PHEVs could in fact be smaller than conventional equivalents.

2.5 Use of biofuels in transportation

**Summary of Main Findings**

- Use of biofuels in transport is supported by a number of policies, including the Biofuels Directive, the Energy Taxation Directive, the Fuel Quality Directive and the Renewable Energy Directive.
- **Fuel lifecycle emissions** show wide variation depending on farming practices, soil, climate conditions and crop characteristics.
  - For first generation biofuels, emissions of PM and SO$_2$-equivalent are increased by 1.5 to 3 times compared to fossil gasoline and diesel, with the exception of biogas which has about the same emissions.
  - Lifecycle emissions from second generation lingo-ethanol are about the same as from gasoline and diesel.
  - Lifecycle emissions of SO$_2$-equivalent from second generation biomass to liquids are almost doubled.
- The effects of biofuels on tailpipe emissions are uncertain.
  - Overall, low blends of bioethanol show a small reduction in air pollutants, with the exception of NO$_x$.
  - Higher strength blends (E85) show smaller reductions still.
  - Biodiesel blends based on vegetable oil lead to reductions in HC, CO and PM, but can result in higher NO$_x$ emissions.
  - Higher strength biodiesel blends show larger changes in emissions.
- Biodiesel blends based on animal fats show greater reductions in PM emissions and smaller increases in NO$_x$ compared to plant-based oils.

The use of biofuels in transportation is being encouraged by several policy initiatives including:
- EU Biofuels Directive;
- Renewable Energy Directive;
- Energy Taxation Directive;

The EU Biofuels Directive (2003/30/EC) sets a European target of 10% substitution of fossil fuels with biofuels by 2020. Although the targets are indicative, they were expected to have a strong political impact. The Renewable Energy Directive (2009/28/EC) set binding targets for renewable energy in transport (10% in all Member States by 2020). The Energy Taxation Directive (2003/96/EC) allows Member States to exempt biofuels from taxation, as they are generally more expensive than mineral fuels and electricity. In 2009, Article 7a of the EU’s Fuel Quality Directive came into force. This Article requires fuel suppliers to reduce lifecycle GHG emissions of the fuel they supply by 6% by 2020. From 2011 unleaded petrol at the pump will contain up to 10% ethanol (E10) as opposed to 5% (E5). Diesel will contain up to 7% fatty acid methyl ester (B7). Sustainability criteria were incorporated for biofuels used to meet the GHG reduction requirement.

In 2010, with the entering into force of Euro 5 standards, the test fuels contain 5% biofuels. Although biofuels are an important options for reducing transport GHG emissions, their effects on air quality are still unclear.

**Fuel lifecycle emissions**

Lifecycle emissions from first generation biofuels, as calculated for EU countries in a report for the ETC (2009), are presented in Table 2.6. These include full upstream activities...
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including farming, transport, fertilizers and processing. There is significant variation in yields depending on farming practices, soil, climate conditions and crop characteristics. In order to account for this variety, a selection of bioenergy crops was considered in different environmental zones. The lifecycle SO$_2$-e and PM emissions of biofuels are 1.5 to 3 times higher than those from fossil diesel and gasoline, apart from biogas which has about the same emissions. However, the impacts of PM emissions are generally over 3 times higher in urban areas compared to rural/low population areas, therefore an increase in lifecycle PM may not result in an increased impact (and could in fact be smaller depending on specific conditions).

Table 2.6: Lifecycle air pollutant emissions from biofuels in EU countries, 2010

<table>
<thead>
<tr>
<th>emissions [g/kWh$_{fuel}$]</th>
<th>SO$_2$ eq.</th>
<th>SO$_2$</th>
<th>NO$_x$</th>
<th>partic.</th>
<th>CO</th>
<th>NMVOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>gasoline</td>
<td>0.33</td>
<td>0.15</td>
<td>0.23</td>
<td>0.02</td>
<td>1.07</td>
<td>0.56</td>
</tr>
<tr>
<td>diesel</td>
<td>0.33</td>
<td>0.13</td>
<td>0.35</td>
<td>0.02</td>
<td>0.29</td>
<td>0.09</td>
</tr>
<tr>
<td>SVO ATC</td>
<td>1.13</td>
<td>0.15</td>
<td>0.64</td>
<td>0.06</td>
<td>0.33</td>
<td>0.06</td>
</tr>
<tr>
<td>FAME ATC</td>
<td>1.19</td>
<td>0.18</td>
<td>0.68</td>
<td>0.06</td>
<td>0.35</td>
<td>0.06</td>
</tr>
<tr>
<td>FAME CON</td>
<td>1.27</td>
<td>0.26</td>
<td>0.78</td>
<td>0.07</td>
<td>0.37</td>
<td>0.07</td>
</tr>
<tr>
<td>FAME MED</td>
<td>1.70</td>
<td>0.25</td>
<td>0.93</td>
<td>0.09</td>
<td>0.42</td>
<td>0.07</td>
</tr>
<tr>
<td>FAME PAN</td>
<td>1.82</td>
<td>0.32</td>
<td>0.95</td>
<td>0.10</td>
<td>0.41</td>
<td>0.07</td>
</tr>
<tr>
<td>ETOH (sugarbeet) ATC</td>
<td>0.93</td>
<td>0.09</td>
<td>0.54</td>
<td>0.04</td>
<td>1.17</td>
<td>0.07</td>
</tr>
<tr>
<td>ETOH (sugarcane)/from-BR</td>
<td>1.10</td>
<td>0.38</td>
<td>0.97</td>
<td>0.15</td>
<td>1.38</td>
<td>0.53</td>
</tr>
<tr>
<td>ETOH (maize) ATC</td>
<td>0.61</td>
<td>0.07</td>
<td>0.37</td>
<td>0.03</td>
<td>1.10</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (maize) ATN</td>
<td>0.61</td>
<td>0.07</td>
<td>0.37</td>
<td>0.03</td>
<td>1.10</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (maize) CON</td>
<td>0.77</td>
<td>0.18</td>
<td>0.50</td>
<td>0.04</td>
<td>1.15</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (maize) MED</td>
<td>0.69</td>
<td>0.09</td>
<td>0.40</td>
<td>0.03</td>
<td>1.11</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (maize) PAN</td>
<td>0.57</td>
<td>0.08</td>
<td>0.41</td>
<td>0.03</td>
<td>1.11</td>
<td>0.05</td>
</tr>
<tr>
<td>ETOH (wheat) ATC</td>
<td>0.62</td>
<td>0.08</td>
<td>0.37</td>
<td>0.03</td>
<td>1.10</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (wheat) ATN</td>
<td>0.65</td>
<td>0.08</td>
<td>0.37</td>
<td>0.03</td>
<td>1.09</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (wheat) CON</td>
<td>0.78</td>
<td>0.19</td>
<td>0.51</td>
<td>0.04</td>
<td>1.10</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (wheat) MED</td>
<td>0.51</td>
<td>0.07</td>
<td>0.42</td>
<td>0.02</td>
<td>1.12</td>
<td>0.04</td>
</tr>
<tr>
<td>ETOH (wheat) PAN</td>
<td>0.59</td>
<td>0.09</td>
<td>0.43</td>
<td>0.03</td>
<td>1.11</td>
<td>0.05</td>
</tr>
<tr>
<td>biogas (double-crop) ATC</td>
<td>0.38</td>
<td>0.03</td>
<td>0.28</td>
<td>0.02</td>
<td>1.37</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Source: ETC (2009)
Notes:  Bioenergy crops: FAME = fatty acid methyl ester from rape seed and sunflower seed;; ETOH = ethanol from maize, sorghum and wheat; SRC = short rotation coppice from poplar & willow; BtL = biomass to liquids from giant reed, miscanthus & switchgrass.  Regions: ATC = Atlantic central (BE, DE, FR, UK); ATN = Atlantic north (FI, SE, EE, LT, LV); CON = continental (AT, PL); MED = Mediterranean (ES, GR, IT, PT); PAN = Pannonian Pontic (CZ, HU, SI, SK).

Second generation biofuels from lignocellulosic feedstocks are expected to become available by 2030. In addition, changes in emissions from electricity have been taken into account. For ethanol, the second generation technology is here assumed to convert the hemicellulosic parts of the plants into ethanol, while burning the remaining lignin for energy. The SO$_2$-equivalent emissions from lingo-ETOH from wheat are about the same as those from fossil fuels. Biomass to liquid fuels result in almost double the SO$_2$-equivalent emissions compared to diesel. Biogas from double cropping and maize has the lowest emissions.
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

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Contract 070307/2010/579469/SER/C2

Table 2.7: Lifecycle air pollutant emissions for second generation biofuels in EU countries, 2030

<table>
<thead>
<tr>
<th>emissions [g/kWh]</th>
<th>SO₂ eq.</th>
<th>SO₂</th>
<th>NOₓ</th>
<th>partic.⁺</th>
<th>CO</th>
<th>NMVOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>gasoline</td>
<td>0.33</td>
<td>0.15</td>
<td>0.22</td>
<td>0.02</td>
<td>1.08</td>
<td>0.55</td>
</tr>
<tr>
<td>diesel</td>
<td>0.37</td>
<td>0.12</td>
<td>0.35</td>
<td>0.02</td>
<td>0.30</td>
<td>0.08</td>
</tr>
<tr>
<td>BtL (SRC) ATC</td>
<td>0.60</td>
<td>0.03</td>
<td>0.78</td>
<td>0.02</td>
<td>0.77</td>
<td>0.07</td>
</tr>
<tr>
<td>BtL (SRC) ATN</td>
<td>0.61</td>
<td>0.03</td>
<td>0.78</td>
<td>0.03</td>
<td>0.78</td>
<td>0.08</td>
</tr>
<tr>
<td>BtL (SRC) CON</td>
<td>0.61</td>
<td>0.03</td>
<td>0.79</td>
<td>0.02</td>
<td>0.78</td>
<td>0.08</td>
</tr>
<tr>
<td>BtL (giant reed) MED</td>
<td>0.58</td>
<td>0.02</td>
<td>0.76</td>
<td>0.02</td>
<td>0.71</td>
<td>0.07</td>
</tr>
<tr>
<td>BtL (miscanthus) MED</td>
<td>0.57</td>
<td>0.02</td>
<td>0.75</td>
<td>0.01</td>
<td>0.71</td>
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</tr>
<tr>
<td>BtL (SRC) PAN</td>
<td>0.65</td>
<td>0.04</td>
<td>0.80</td>
<td>0.02</td>
<td>0.78</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (maize) ATC</td>
<td>0.50</td>
<td>0.06</td>
<td>0.27</td>
<td>0.01</td>
<td>1.16</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (maize) ATN</td>
<td>0.52</td>
<td>0.06</td>
<td>0.26</td>
<td>0.01</td>
<td>1.16</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (maize) CON</td>
<td>0.47</td>
<td>0.07</td>
<td>0.35</td>
<td>0.01</td>
<td>1.19</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (maize) MED</td>
<td>0.47</td>
<td>0.07</td>
<td>0.32</td>
<td>0.01</td>
<td>1.17</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (maize) PAN</td>
<td>0.47</td>
<td>0.07</td>
<td>0.32</td>
<td>0.01</td>
<td>1.17</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (wheat) ATC</td>
<td>0.40</td>
<td>0.06</td>
<td>0.26</td>
<td>0.01</td>
<td>1.16</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (wheat) ATN</td>
<td>0.36</td>
<td>0.05</td>
<td>0.25</td>
<td>0.01</td>
<td>1.15</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (wheat) CON</td>
<td>0.50</td>
<td>0.06</td>
<td>0.32</td>
<td>0.01</td>
<td>1.19</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (wheat) MED</td>
<td>0.34</td>
<td>0.05</td>
<td>0.29</td>
<td>0.01</td>
<td>1.17</td>
<td>0.08</td>
</tr>
<tr>
<td>EtOH-Ighno (wheat) PAN</td>
<td>0.35</td>
<td>0.07</td>
<td>0.30</td>
<td>0.01</td>
<td>1.16</td>
<td>0.09</td>
</tr>
<tr>
<td>biogas (double-crop) ATC</td>
<td>0.28</td>
<td>0.02</td>
<td>0.21</td>
<td>0.01</td>
<td>1.36</td>
<td>0.01</td>
</tr>
<tr>
<td>biogas (maize) ATC</td>
<td>0.34</td>
<td>0.02</td>
<td>0.16</td>
<td>0.01</td>
<td>1.34</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Source: ETC (2009)
Notes: Bioenergy crops: EtOH = maize, sorghum & wheat for biomass & bioethanol; SRC = short rotation coppice from poplar & willow as a solid fuel and feedstock for gasification; BtL = giant reed, miscanthus & switchgrass as solid fuels and feedstocks for biomass to liquids; double cropping systems for bioethanol. Regions: ATC = Atlantic central (BE, DE, FR, UK); ATN = Atlantic north (FI, SE, EE, LT, LV); CON = continental (AT, PL); MED = Mediterranean (ES, GR, IT, PT); PAN = Pannonic Pontic (CZ, HU, SI, SK).

2.5.1 Use of ethanol blends in petrol vehicles

It is estimated that 90-95% of current petrol vehicles can run on E10 (10% ethanol blends), and the remaining vehicles can use E5 (TNO, 2008). Higher blends of up to 85% can only be used in flexible fuel vehicles. Other bio-components such as bio-ETBE, biopetrol and butanol have better compatibility with petrol than ethanol, but large-scale production still needs to be demonstrated (TNO, 2008). The data in Table 2.8 shows there is significant variation in NOₓ emission levels when ethanol blends are used (from -50% to +300%), therefore it is not possible to draw conclusions based on this evidence. However, NOₓ emissions are generally low compared to diesel engines. Hydrocarbon (HC) emissions also show variation between positive and negative values.

Table 2.8: Effect of ethanol blends on NOₓ and HC emissions of passenger car petrol engines

<table>
<thead>
<tr>
<th>Petrol passenger cars – NOₓ emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel blend</td>
</tr>
<tr>
<td>E5</td>
</tr>
<tr>
<td>E10 – E20</td>
</tr>
<tr>
<td>E40 – E85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Petrol passenger cars – HC emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel blend</td>
</tr>
<tr>
<td>E5</td>
</tr>
<tr>
<td>E10 – E20</td>
</tr>
<tr>
<td>E40 – E85</td>
</tr>
</tbody>
</table>

Source: TNO, 2008
As shown in Figure 2.27, the influence of ethanol blend % on NO$_x$ emissions shows a high variance. This is due to the low NO$_x$ emissions of petrol engines, which are often far below the limit values, meaning that the dataset is skewed towards the positive side (CE Delft, 2009). These figures can therefore be taken as the worst case scenario.

**Figure 2.27: Influence of ethanol blend % on NO$_x$ emissions for light duty vehicles**

![Graph showing influence of ethanol blend on NO$_x$ emissions](image)

Source: CE Delft (2009)

Other research (summarised in Defra, 2011) shows that low strength bioethanol generally leads to no change in NO$_x$, but reductions in CO and PM. These benefits are more pronounced for older cars without emission controls. At high strengths (E85), the evidence is inconclusive. The results are likely to be affected by factors such as engine retuning and the physical characteristics of the fuel. Approximate scaling factors are shown in Table 2.9

**Table 2.9: Emission scaling factors for blends of ethanol**

<table>
<thead>
<tr>
<th>Fuel blend</th>
<th>HC</th>
<th>CO</th>
<th>NO$_x$</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5</td>
<td>0.975</td>
<td>0.9</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>E10</td>
<td>0.950</td>
<td>0.8</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>E15</td>
<td>0.925</td>
<td>0.7</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>E85</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Source: Defra (2011)

Overall, the Defra (2011) work indicates low blends of ethanol are expected to have small positive effects on air quality. Higher strength blends show smaller benefits; however, more research is required to improve understanding.

### 2.5.2 Use of biodiesel blends in diesel vehicles

Large variations have been found for both particulates and NO$_x$ emissions from cars running on biodiesel blends depending on the biofuel properties and engine technology (TNO, 2008). Synthetic diesel, such as from Hydrotreated Vegetable Oil (HVO) and Biomass to Liquids (BtL) pathways, can be used instead of fatty acid methyl ester (FAME). These synthetic diesel fuels are more sustainable sources that can be blended in any percentage without affecting engine durability. Emissions are generally reduced for both NO$_x$ and particulates in the range of 0-30% when using synthetic diesels.
Table 2.10: Effect of biofuel blends on NO\textsubscript{x} and PM emissions of passenger car diesel engines

<table>
<thead>
<tr>
<th>Fuel blend</th>
<th>&lt; Euro 3</th>
<th>Euro 4</th>
<th>Euro 5</th>
<th>Euro 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5 – B10</td>
<td>0% to – 20%</td>
<td>Some decrease/increase possible</td>
<td>No effect from B5. Increase or decrease possible with B10</td>
<td></td>
</tr>
<tr>
<td>B20 – B100</td>
<td>- 10% to + 20%</td>
<td>- 10% to + 20%</td>
<td>Risk of larger variation with some vehicle types</td>
<td></td>
</tr>
<tr>
<td>Pure HVO XTL</td>
<td>0% to – 20%</td>
<td>0% to – 20%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Notes: BX = X% fatty acid methyl ester in diesel; HVO = hydrotreated vegetable oil; XTL = gas to liquid or biomass to liquid

The measured emissions for all vehicle types show great uncertainties. However, emissions are expected to improve due to the formal emission requirements for biofuels (E5 and B5) introduced as part of Euro 5 (2010). Future diesel engines are expected to be equipped with particulate filters and closed-loop NO\textsubscript{x} control, thus the potential negative impacts are likely to disappear.

In a recent review of biofuels literature, Defra (2011) notes that most types of biodiesel from esterified vegetable oils (i.e. FAME) lead to reductions in HC, CO and PM, but can result in higher NO\textsubscript{x} emissions. The changes can become larger for higher percentages of biodiesel. Esterified diesel blends made from animal fat show greater reductions in PM and smaller increases in NO\textsubscript{x} compared to blends based on vegetable and plant oils. Virgin plan oils can be used in pure form or in blends. The scaling factors shown are very approximate as only a small number of studies have been carried out.

Table 2.11: Emission scaling factors for blends of biodiesel (light duty vehicles)

<table>
<thead>
<tr>
<th>Fuel blend</th>
<th>HC</th>
<th>CO</th>
<th>NO\textsubscript{x}</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5</td>
<td>0.97</td>
<td>0.99</td>
<td>1</td>
<td>0.95</td>
</tr>
<tr>
<td>B10</td>
<td>0.95</td>
<td>0.89</td>
<td>1</td>
<td>0.91</td>
</tr>
<tr>
<td>B15</td>
<td>0.92</td>
<td>0.97</td>
<td>1</td>
<td>0.86</td>
</tr>
<tr>
<td>B100</td>
<td>0.31</td>
<td>0.66</td>
<td>1.08</td>
<td>0.62</td>
</tr>
<tr>
<td>Virgin plant oil</td>
<td>1.50</td>
<td>1.50</td>
<td>1</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Source: Defra (2011)

While the changes in CO and HC are demonstrated consistently for biodiesel blends, the changes in NO\textsubscript{x} and PM are less certain.
2.6 Non-technical measures

Summary of Main Findings

⇒ Passenger car taxation can be linked to CO₂ emissions to encourage uptake of more fuel efficient vehicles and electric vehicles. If these new cars directly replace older cars, emissions of regulated pollutants are likely to be reduced because newer cars would adhere to stricter Euro standards.
⇒ Other schemes provide monetary incentives for electric vehicles, which would reduce local pollutant emissions, but has an uncertain effect on overall emissions.
⇒ Unintended negative consequences of incentivising purchase of new vehicles is that it could lead to purchase of vehicles which would not otherwise have been bought, thereby increasing overall emissions.
⇒ Differentiating fuel taxes according to carbon content may encourage a shift to low carbon vehicles.
⇒ Driving styles can affect exhaust emissions; therefore programs which encourage best practice driver behaviour can deliver significant air quality benefits.
⇒ Attempts to measure the effects have produced inconsistent results due to the difficulty in standardising driver behaviour.
⇒ For conventional ICE vehicles, eco-driving and speed reduction can produce fuel efficiency savings of 8-25%. Tailpipe emissions will be reduced in proportion to the saved fuel.
⇒ Aggressive driving can increase NOₓ emissions by 2-5 times and CO by 3-4 times.
⇒ Driving at high speeds on motorways emits around 30% more NOₓ per km for cars and LGVs compared to driving on rural and urban roads.
⇒ For cars, emissions of PM per km are the same on urban roads and motorways, and 30% lower on rural roads. For LGVs, emissions of PM per km are highest on urban roads, 24% lower on motorways, and 44% lower on rural roads.

2.6.1 Economic instruments

There are a range of economic instruments available that are aimed at reducing GHG emissions from vehicles. Passenger car taxation can be banded to incentivise the purchase and use of lower emission vehicles. The objective of linking the passenger car taxation to a vehicle’s CO₂ emissions is to provide a clear price signal to consumers and manufacturers alike in order to stimulate both supply to market and then uptake of lower emission vehicles. At present, 17 member states employ some form of banded passenger car taxation: Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Ireland, Latvia, Luxembourg, Malta, the Netherlands, Portugal, Romania, Spain, Sweden and the United Kingdom (ACEA, 2010). The existing CO₂-linked taxation systems can take different forms. These include:
  • Registration tax, levied when a new vehicle is first registered for use (e.g. France, Portugal);
  • Circulation tax, levied on an annual basis (e.g. Denmark, Sweden);
  • Company car tax, which applies on the company vehicles (e.g. Belgium, the United Kingdom).

These schemes incentivise the purchase of newer ICE vehicles, which must adhere to the most recent Euro standards. If these new cars replace older cars like-for-like, emissions of regulated pollutants are likely to be reduced. Emissions of sulphur will also reduce due to the lower fuel consumption. Higher uptake of electric, hydrogen fuel cell and hybrid vehicles could also result (the effects of these vehicle types on emissions are discussed in section...
2.4). However, these incentives may stimulate the purchase of cars that would not otherwise have been bought, and this could increase overall emissions.

Many countries have also introduced monetary incentives for the purchase of electric vehicles. The range and magnitude of incentives wide and may consist of reductions in taxes (registration, circulation, personal income or company car taxes), exemptions from taxes, or grants (ACEA, 2011). Some countries use a combination of different measures; for example Portugal awards a premium for purchased of electric vehicles, as well as exempting them from circulation and registration taxes. Section 2.4.2 details the relative emissions of electric vehicles compared to conventional cars. In general, for each conventional vehicle that is replaced by an electric vehicle, local emissions will reduce but the effects on upstream emissions are uncertain. As with purchase incentives for low CO$_2$ vehicles, overall emissions (GHG and air quality) could be increased if it leads to uptake of cars that would not otherwise have been purchased. In the case of electric vehicles, which are primarily used in urban areas, there is potentially a higher risk of modal shift from non-motorised modes or public transport, particularly if the scheme is coupled with other incentives such as exemption from congestion charges or access to free parking.

In Europe, the costs of climate change will be internalised by differentiating fuel taxes according to carbon content. A single minimum rate for CO$_2$ emissions of €20 per tonne CO$_2$ is proposed for all sectors not covered by the EU ETS. The other component of the minimum taxation rate is based on energy content, set at €9.6 per GJ for motor fuels. This could encourage higher uptake of electric, hydrogen fuel cell and hybrid vehicles (the effects of these vehicle types on emissions are discussed in section 2.4).

### 2.6.2 Driving profiles

It is well known that driving profiles influence exhaust emissions (both GHG and air quality). For example, harsh acceleration and using the gears instead of the brakes to slow down the vehicle leads to increased emissions (Bell, 2006). The influence of driving behaviour makes it difficult to compare the impacts of vehicles with each other in the real world.

**Eco-driving** involves training drivers to modify their driving style in a way that reduces fuel consumption and emissions. This may involve actions such as timely gear changes, smooth deceleration and anticipation of traffic flows. TNO (2004) evaluated the effect of driving style tips used as part of the Dutch Ecodriving initiative. Three tips were evaluated:

1. Shift as soon as possible at a maximum of 2500 r/min (2000 r/min for a diesel) to as high a gear as possible;
2. Press the throttle quickly and vigorously as much as it takes to keep up with the traffic; and
3. Do not shift down to a lower gear too early and keep the car rolling without disengaging the clutch, and in as high a gear as possible.

Tips 1 and 3 resulted in reductions of NO$_x$ emissions of 55% in urban conditions and 47% in extra urban conditions for petrol cars. For diesel cars, tips 1 and 3 resulted in NO$_x$ emissions that were 29% lower in extra urban conditions, but results in urban conditions were not consistent. The use of all tips in extra urban conditions was found to actually increase emissions of NO$_x$ by 55% for petrol cars, and by 11% for diesel cars, mainly due to misinterpretation of tip #2 which was considered to be somewhat counterintuitive. The impact of the tips on PM was assessed for diesel vehicles: Tips 1 and 3 reduced PM emissions by 27% in urban conditions and by 31% in extra urban conditions. The use of all

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tips was found to be beneficial in urban conditions (18% improvement in PM emissions) but detrimental in extra urban conditions (6% increase in PM emissions).

Tzirakis (2007) measured the difference between aggressive and defensive driving styles on emissions from 12 vehicles in real conditions. The results showed that emissions of CO HC and NO were increased for almost all vehicles when using an aggressive style of driving. The vehicles varied in age, mileage, engine displacement and technology (from Euro 1-5). Similarly, Bell (2006) found that aggressive driving can cause emissions of NO\textsubscript{x} to be 2-5 times higher, and CO emissions to be 3-4 times higher.

Experience suggests that communication campaigns, supported by information materials, can improve fuel efficiency by around 5% for people who follow the advice (IEA, 2007). While many studies confirm the initial benefits, the long-term effects are less well-documented and are likely to be smaller. Longevity may be increased by follow-up measures; fuel savings (hence emission impacts) over the medium term (<3 years) are reported to be around 5% where there were no follow up measures, or 10% where continuous feedback was available (IEA, 2007).

The impact of driving speed is also significant. The UK NAEI (2011) estimates emission factors for based on test data for in-service vehicles over a range of different drive cycles. The emissions are for the average speeds and road type, modelled using the UK fleet composition and journeys made in 2008. Cars and Light Goods Vehicles (LGVs) tend to emit the highest levels of NO\textsubscript{x} per km on motorways, and the lowest levels on rural roads. Emissions of NO\textsubscript{x} on urban roads are only slightly higher than for rural roads.

**Figure 2.28:** NO\textsubscript{x} emissions factors for hot exhaust and cold start, by road type

![NO\textsubscript{x} emissions factors for hot exhaust and cold start, by road type](image)

**Source:** NAEI (2011)

**Notes:** Hot exhaust emissions are tailpipe emissions from a vehicle with its engine warmed up to normal operating temperature. Cold start exhaust emissions are additional tailpipe emissions from a vehicle starting a journey with its engine cold. Average speeds are: urban – 48.27 km/h; rural – 77.232 km/h; motorway – 112.63 km/h.

Emissions of SO\textsubscript{2} are estimated to be constant on all road types, at 0.002g/km for all cars, and 0.001g/km for LGV. Although actual emissions are likely to be smallest on rural roads (due to lower fuel consumption per km), any differences do not show up as the numbers have been rounded to 3 decimal places (UK NAEI, 2011).

Around 51% of PM emissions are made up of coarse PM\textsubscript{10} and the remainder is PM\textsubscript{2.5}. For cars, emissions of PM per km are the same on urban roads and motorways, and 30% lower
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

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on rural roads. For LGVs, emissions of PM are highest on urban roads, 24% lower on motorways, and 44% lower on rural roads.

Figure 2.29: PM$_{10}$ and PM$_{2.5}$ emission factors for hot exhaust and cold start, by road type

![Diagram showing PM emission factors by road type]

Source: NAEI (2011)

Notes: Hot exhaust emissions are tailpipe emissions from a vehicle with its engine warmed up to normal operating temperature. Cold start exhaust emissions are additional tailpipe emissions from a vehicle starting a journey with its engine cold. Average speeds are: urban – 48.27 km/h; rural – 77.23 km/h; motorway – 112.63 km/h.

Speed-emission curves calculated for the UK car fleet are shown in Figure 2.30 and Figure 2.31. Projections out to 2035 are also calculated, which shows the expected improvement in tailpipe emissions over time. In 2010, petrol cars emit around 0.35 gNOx/km when travelling at 5 km/h. This drops to around 0.12 gNOx/km at its lowest point (40 km/h) and gradually rises again to 0.15 gNOx/km at higher speeds of 90 km/h. By 2035, these figures are expected to drop to 0.11 gNOx/km (5 km/h), 0.05 gNOx/km (40 km/h) and 0.06 gNOx/km (90 km/h). Diesel cars in the average UK fleet emit higher levels of NOx compared to petrol cars. In 2010, diesel cars emit around 1.57 gNOx/km when travelling at 5 km/h. The lowest levels are 0.35 gNOx/km when travelling at 55 km/h, rising again to 0.39 gNOx/km at 90 km/h. By 2035, these figures fall to 0.36 gNOx/km (5 km/h), 0.08 gNOx/km (55 km/h) and 0.10 gNOx/km (90 km/h).

Figure 2.30: NOx speed-emission curves for UK car fleet

![Diagram showing NOx emissions by speed for petrol and diesel cars]

Source: NAEI (2011)

Notes: The PM emissions from petrol cars form a curve with a similar shape to the NOx emissions, with the highest emissions of 0.0054 gPM/km at 5 km/h and the lowest emissions of 0.0016 gPM/km at 40 km/h for the UK 2010 average fleet. For diesel cars, emissions of PM are 0.071 gPM/km at 5 km/h and the lowest emissions of 0.022 gPM/km at 50 km/h.
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

Figure 2.31: PM speed-emission curves for UK car fleet

Source: NAEI (2011)

Figures for SOx emissions were not directly available, but these are dependent on fuel sulphur content and will therefore scale directly with fuel consumption which is shown in Figure 2.32

Figure 2.32: Fuel consumption curves for UK car fleet

Source: NAEI (2011)

Lower speed limits on motorways should reduce fuel consumption and pollutant emissions. Assuming smooth driving and total compliance with speed limits, the EEA (2011c) estimated that reducing the motorway speed limit for current passenger cars from 120 to 110 km per hour would reduce fuel consumption by 12 % for diesel cars and 18 % for gasoline cars. Under more realistic assumptions (including sub-optimal driving patterns, and traffic congestion) the actual fuel savings would be 2-3%.
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

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Figure 2.33: Impact of travelling speed on fuel consumption (Euro 4 diesel and gasoline passenger cars, 1.4–2.0 litre engine capacity)

Source: EEA, 2011c

Figures 3 and 4 show that reducing speed in the above range has a beneficial effect for all pollutants except for CO (in the case of diesel vehicles) and NOx (in the case of gasoline vehicles). The benefits of reducing average speed from 100 km/h to 90 km/h range from 25% (gasoline CO) to 5% (diesel PM). Crucially, decreasing speed reduces the two pollutants currently most important in Europe: diesel NOx and PM.

Reducing speed leads to lower levels of all pollutants except for CO (diesel) and NOx (gasoline). However, diesel vehicles are minor contributors of CO, and CO is not considered a problem for air quality in Europe (EEA, 2011c). For gasoline cars, increasing speed results in lower relative NOx emissions up to around 115 km/h, after which point emissions start to trend upward. However, diesel cars emit higher levels of NOx with increasing speed. Since the level of NOx emissions from diesel cars is much higher (560mg/km for diesel compared to 19mg/km for petrol, at 100km/h), the overall effect of lowering speed limits on motorways would be to reduce NOx emissions.

Figure 2.34: Impact of travelling speed on various pollutants (Euro 4 passenger cars, 1.4–2.0 litre engine capacity)

Source: EEA, 2011c

A practical example of speed control in Europe is demonstrated by Overschie in Rotterdam (2002). The speed limit was reduced from 120km/h to 80 km/h on a 3.5km stretch of motorway. Enforcement measures were introduced to ensure compliance through the use of cameras and average speed checks, with only a 2% offense rate. Emissions were reduced by 15-25% for NOx, 25-35% for PM10 and 21% for CO (EEA, 2008).
2.6.3 Provision of consumer information

Directive 1999/94/EC is concerned with the availability of consumer information on fuel economy and CO\textsubscript{2} emissions in respect of the marketing of new passenger cars. The purpose of the Directive, as stated in its Article 1, “is to ensure that information relating to the fuel economy and CO\textsubscript{2} emissions of new passenger cars offered for sale or lease in the Community is made available to consumers in order to enable consumers to make an informed choice”. The Directive requires information on fuel economy and CO\textsubscript{2} emissions to be displayed in the following ways:

- A fuel economy label for all new cars to be displayed at the point of sale.
- A guide on fuel economy and CO\textsubscript{2} emissions that should be available at the point of sale and from designated bodies.
- A poster (or a display) showing the official fuel consumption and CO\textsubscript{2} emissions data of all new passenger car models displayed or offered for sale or lease at, or through, the respective point of sale.
- All promotional literature must contain the official fuel consumption and specific CO\textsubscript{2} emission data for the passenger car model to which it refers\textsuperscript{16}.

Directive 1999/94 was always meant to work in conjunction with supply-side policies (i.e. first the voluntary agreements, then Regulation 443/2009) and demand-side instruments, such as vehicle taxation, as part of a wider strategy. In this respect, it is not surprising that it is difficult to identify the impact of the label on its own, which was the conclusion of the first study on the effectiveness of the Directive (ADAC, 2005)\textsuperscript{17}. As was reported in the review of relevant literature undertaken for the European Parliament study (EP, 2010), other authors have also reached this conclusion, with Anable \textit{et al} (2008) arguing that the provision of fuel economy information is necessary but not sufficient to influence consumers' choices\textsuperscript{18}.

The literature reviewed for the European Parliament study concluded that the provision of information is most effective when linked to financial incentives. A number of Member States (e.g. the UK) have, therefore, linked a revised label, i.e. one that goes beyond the requirements of the Directive, to their circulation taxes. The label can also be used for the purpose of a short-term incentive, as has been done in the Netherlands (see TNO \textit{et al}, 2006).

Therefore, the provision of consumer information on the CO\textsubscript{2} emissions of new passenger cars, in conjunction with supply-side policies and demand-side instruments may have a positive effect on reducing CO\textsubscript{2} emissions. This may subsequently have an effect on air pollutant emissions is the lower polluting/more fuel efficient models are purchased.


\textsuperscript{18} Anable, Jillian \textit{et al.} (2008): “Car buyer survey: From ‘mpg paradox’ to ‘mpg mirage’: How car purchasers are missing a trick when choosing new and used cars” (Final report). Research conducted on behalf of the Low Carbon Vehicle Partnership.
2.7 Non-exhaust air pollutant emissions

Summary of Main Findings

1. Currently, brake and tyre wear accounts for 46-55% of PM\(_{10}\) emissions, and 33-41% of PM\(_{2.5}\) emissions from cars. For LGVs, brake and tyre wear accounts for 21-32% of PM\(_{10}\) emissions and 13-22% of PM\(_{2.5}\). Non-exhaust emissions are made up of tyre and brake wear and will account for a larger proportion of overall vehicle emissions as new vehicles reduce their exhaust emissions in line with the Euro standards or through the utilisation of electric drive trains.

2. PM\(_{10}\) makes up the majority of tyre wear emissions, accounting for around 59%, with PM\(_{2.5}\) making up the remainder.

3. Tyre wear emissions are highest from articulated HGVs in particular, but rigid HGVs and buses also emit significant levels. They are lowest for cars and motorcycles.

4. PM\(_{10}\) makes up the majority of tyre wear emissions, accounting for around 71%, with PM\(_{2.5}\) making up the remainder.

5. Brake wear emissions are highest from buses, and lowest from cars and motorcycles.

6. Options for abatement include:
   a. Increased use of regenerative braking – e.g. in hybrid and electric vehicles
   b. Improved materials – hardwearing tyre and brake surface compounds;
   c. Particle collection and destruction – enclosed brakes/wheels, filtration, electrostatic precipitation;
   d. Road and vehicle cleaning; and
   e. Improved inspection and maintenance.

This section focuses on non-exhaust particulate emissions related to brake and tyre wear, since these are the primary non-exhaust air pollutant emissions of significance. There is currently no European legislation which deals directly with emissions from these sources; however Directive 98/12/EC enforces asbestos-free brake pads for all road vehicles. Development of low-friction tyres for fuel efficiency reasons may have a positive effect on particulate emissions.

Brake and tyre wear account for a significant proportion of total PM emissions from cars. Figures from the UK NAEI (2011) suggest that typical non-exhaust PM from cars is around 0.015gPM\(_{10}\)/km and 0.008 gPM\(_{2.5}\)/km. For comparison, hot exhaust emissions for cars are around 0.012 - 0.017gPM\(_{10}\)/km and 0.011 - 0.016 gPM\(_{2.5}\)/km. Therefore, brake & tyre wear account for 46-55% of PM\(_{10}\) emissions, and 33-41% of PM\(_{2.5}\) emissions. For LGVs, the proportion of non-exhaust emissions is lower, but still significant. Typically, brake and tyre wear account for 21-32% of PM\(_{10}\) emissions and 13-22% of PM\(_{2.5}\). As the exhaust emissions of new vehicles improve, non-exhaust emissions will constitute a greater proportion of total emissions from road transport.

2.7.1 Tyre wear

Tyre wear particles range in size from 0.01 – 30 µm. The size distribution has varied in different studies and results are inconclusive. Some have reported up to 90% of mass below 1 µm; others found particles were all above 2.5 µm (Boulter & Ntziachristos (2009)).

The rate of wear depends on driving style, tyre position, vehicle traction configuration, weather and the tyre material, condition and age. There are a wide range of wear factors that have been reported for light duty vehicles as demonstrated in Table 2.12. Wear factors per vehicle-km are shown in Table 2.12 (Boulter & Ntziachristos (2009)).
Tyres are more resistant to wearing if they are more rigid, have better wet grip, and are radial ply as opposed to cross ply. Tyres tend to wear more quickly in urban conditions (due to the greater number of turns) and under aggressive driving styles. Increasing friction between the tyre and the road also increases wear rates, for example when the tarmac is new or weather conditions are dry.

Data from the UK National Atmospheric Emissions Inventory (2011) shows that tyre wear emissions are highest from heavier vehicles such as articulated HGVs, rigid HGVs and buses. Emissions of PM$_{10}$ account for 59% of total tyre wear PM emissions.

**Figure 2.35: Tyre wear emission factors by vehicle type**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>TSP</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-wheelers</td>
<td>8.3</td>
<td>6.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Passenger cars</td>
<td>18.2</td>
<td>12.8</td>
<td>7.4</td>
</tr>
<tr>
<td>Light duty trucks</td>
<td>28.6</td>
<td>21.6</td>
<td>11.7</td>
</tr>
<tr>
<td>Heavy duty trucks</td>
<td>77.7</td>
<td>59.0</td>
<td>31.6</td>
</tr>
</tbody>
</table>


*Notes:* TSP = total suspended particulates

2.7.2 Brake wear

A significant proportion of particular matter from brake wear is emitted as PM$_{10}$ and PM$_{2.5}$, see Table 2.12 (Boulter & Ntziachristos, 2009). Various studies have recorded that between 50% to 90% of total wear material is in the form of airborne particles, depending on the braking severity (Boulter & Ntziachristos, 2009).

The relative position of the brakes on vehicles is an important determinant of the wear rate. In passenger cars the braking force is concentrated in the front wheels, with the rear brakes providing stability. Wear rates are estimated to be around 8.8-20mg/vehicle km for cars, and significantly more for heavy goods vehicles (Boulter & Ntziachristos, 2009). Severe braking events have a large impact on the amount of material lost.

Data from the UK National Atmospheric Emissions Inventory (2011) shows that brake wear emissions are highest from buses, probably due to the high number of braking/acceleration cycles. Emissions of PM$_{10}$ account for 71% of total brake wear PM emissions.
2.7.3 Abatement of non-exhaust air pollutants

Quantitative estimates of abatement of non-exhaust air pollutants were not available, therefore this section provides a qualitative overview with regards to the impacts on emissions of non-exhaust air pollutants.

One way in which air pollutant emissions from brake and tyre wear can be reduced is through increased uptake and use of electric and hybrid vehicles. Electric and hybrid vehicles often use regenerative braking systems. Regenerative braking systems aim to capture some of the kinetic energy which is lost as a vehicle slows down, and is usually dissipated as heat from the brake pads. Recently, regenerative braking systems have been developed for hybrid vehicles which have electric motors. Instead of using friction to slow the vehicle, hybrid cars can make use of their electric motors at slower speeds by reversing the direction of the electric motor, thereby creating a resistance to the forward momentum of the car and generating electrical energy which can be stored in a battery for later use at the same time. The wear on brake pads is reduced, and associated PM emissions are also reduced.

TRL (2006) discusses several abatement measures for non-exhaust emissions. The review found little quantitative information for the effectiveness of the measures was given in the literature.

- **Hardwearing materials** are technically feasible and already deployed in some cases.
- **Particulate collection** would be the responsibility of vehicle manufacturers, who are not currently obliged to introduce this technology and therefore unlikely to do so.
- Other **improvements to the vehicle design** which do not directly control PM are unlikely to have significant impact. The exception is the use of regenerative braking.
- Studies on the effectiveness of **road washing** have produced mixed results – certification of sweepers is needed to guarantee improvements.
- **Vehicle cleaning** is thought to be effective because it reduces the amount of material deposited on the roads.
- **Improved inspection and maintenance** may reduce wear slightly. Other measures such as the use of dust suppressants and the regulation of agricultural practices are mentioned, but not assessed in detail.
2.8 Potential impacts of a limited number of selected GHG reduction options in overall air pollutant emissions from transport

Work currently in progress. To be completed after the November 2011 Focus Group meeting.
3 Environmental Noise Co-Benefits of GHG Reduction Policies

Objectives:
The purpose of this sub-task was to:

- Provide a better understanding of the environmental noise co-benefits of GHG reduction policies for road and railways

Summary of Main Findings
⇒ All GHG policies that reduce vehicle speeds, engine speeds and traffic intensity can substantially reduce road and railway traffic noise and the exposed population.
⇒ GHG policies aimed at reducing emissions in urban areas by access restriction have potentially large traffic noise reductions and take immediate effect both for road and rail.
⇒ Introduction of electric, fuel cell and hybrid powertrains will generally reduce environmental noise, but take 12 years to reach full impact on average road traffic noise levels, mostly in urban areas. For railways the effect is smaller to the predominance of rolling noise. The effect will mainly be for lower speeds and in acceleration and stationary idling conditions.

3.1 Introduction and approach GHG Policy and legislation that affects noise

Transport is the major source of environmental noise pollution in the EU. Noise generation from both road and railway traffic is influenced by vehicle type, speed, traffic intensity, road and track type, road and rail surface conditions, maintenance and usage. Also, the time and route of operation is a factor that determines the average exposure levels, in particular night time freight haulage is a critical issue for both road and rail.

GHG abatement policies are relevant for environmental noise in several respects. The most relevant GHG abatement policies in this context are the following:

- Regulations and incentives for energy saving and emission reducing vehicle design, including electric, hydrogen and hybrid powertrains, tyres with less rolling resistance, reduced aerodynamic drag;
- Regulations on enforcement including MOT and spot checks on vehicle condition and emissions;
- Incentives to reduce use of older vehicles such as scrapping or retrofit programmes;
- Tax incentives to encourage purchase of environmentally friendly vehicles;
- Activity reducing policies, such as road closing in city centres and encouraging use of public transport;
- Restrictions on access times, location or routing for vehicles with lower environmental performance;
- Campaigns and incentives to encourage energy efficient driving.

These abatement policies can be classified in terms of their effect on noise in terms of driving behaviour and management, vehicle design, traffic flow control, infrastructure measures, legislation and incentives. Then the relevant noise source and influence parameters can be identified. This is set out in Table 3.1 below for a range of GHG abatement measures.
The EU regulations on engine emissions may not always affect noise, unless they impact the engine design significantly, especially engine type, power and running speed. There is separate EU/UNECE regulation of vehicle noise emission for new vehicles put onto the market.

The other GHG policies mentioned above have varying affect on traffic noise levels and are mostly implemented by local or national authorities. The subsidiarity principle implies that it is not necessary to regulate these policies at EU level if they are best managed nationally or locally.

A matrix of GHG abatement measures and their relation with key parameters for noise is given in table 2 below. These are explained is the following sections.

Table 3.1 : Matrix of GHG abatement measures and their relation with key parameters for noise, both for road and rail

<table>
<thead>
<tr>
<th>GHG Abatement measure</th>
<th>Main effect on noise</th>
<th>Noise affected source</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving behaviour and management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy efficient driving</td>
<td>Reduced engine and vehicle speeds and thereby noise levels, reduced braking noise for trains</td>
<td>Powertrain noise, braking noise for trains</td>
<td>Engine speed, braking speed and force</td>
</tr>
<tr>
<td>Lower vehicle speeds</td>
<td>Significant effect on noise 20-30 lg (speed)</td>
<td>Powertrain and rolling noise</td>
<td>Engine and vehicle speed</td>
</tr>
<tr>
<td>Lower engine speeds</td>
<td>Significant effect on noise 30 lg (engine speed)</td>
<td>Powertrain noise</td>
<td>Engine speed</td>
</tr>
<tr>
<td>Use of tyres with lower rolling resistance</td>
<td>No direct relation with noise, but combined quieter and energy saving tyre is possible</td>
<td>Rolling noise</td>
<td>Nominal tyre noise level</td>
</tr>
<tr>
<td><strong>Vehicle design measures</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust treatment/catalyst</td>
<td>May increase noise without countermeasures, due to higher temperature and flow resistance.</td>
<td>Powertrain noise</td>
<td>Engine speed, flow resistance</td>
</tr>
<tr>
<td>Reduction of engine losses</td>
<td>Noise reduction may also result</td>
<td>Powertrain noise including cooling fan</td>
<td>Nominal noise level of engine</td>
</tr>
<tr>
<td>Smaller vehicles, lower mass</td>
<td>May sometimes be quieter depending on engine design and operation</td>
<td>Powertrain and rolling noise</td>
<td>Engine and vehicle speed, no. of wheels</td>
</tr>
<tr>
<td>Electric powertrain</td>
<td>Significantly lower noise levels</td>
<td>Powertrain noise</td>
<td>Nominal noise level of engine</td>
</tr>
<tr>
<td>Hydrogen fuel cell powertrain</td>
<td>Significantly lower noise levels</td>
<td>Powertrain noise</td>
<td>Nominal noise level of engine</td>
</tr>
<tr>
<td>Hybrid powertrain</td>
<td>General lower noise level except for acceleration and recharging cycle</td>
<td>Powertrain noise</td>
<td>Engine speed</td>
</tr>
<tr>
<td>Reduced drag</td>
<td>Lower noise emission for high speeds</td>
<td>Aerodynamic noise, esp. trains</td>
<td>Vehicle speed and drag</td>
</tr>
</tbody>
</table>
Background and impact of environmental noise from road and railway traffic

Environmental noise from road and railway traffic is dominated by a number of types of noise source. For road traffic these are primarily tyre noise and powertrain noise. For railways, they are wheel-rail rolling noise, powertrain noise, aerodynamic noise, curve squeal, impact noise and braking noise. The typical situations where they impact the population are close to roads and railway lines with any significant traffic flow, both in urban and rural areas. Urban areas are affected most due to the large numbers of residents, length of urban roads and traffic intensity. Although motorways and high speed lines are a major noise source, most people affected by traffic noise live near arterial roads, main or residential roads or conventional railway lines. Motorways are actually only about 2% of the total road network of 5 million km in the EU27 and urban motorways only 0.1%. In urban areas there are typically more intermittent sources due to accelerating and decelerating traffic, curves and junctions which are less frequent outside those areas.

Environmental noise from roads and railways is evaluated in terms of the day-evening-night average level $L_{DEN}$ and the night time level $L_{night}$. Both are calculated from traffic parameters for noise mapping. The night levels are most relevant for sleep disturbance. Numbers of seriously annoyed and sleep disturbed people can be derived from existing dose-effect relationships.

Besides the $L_{DEN}$ and $L_{night}$, which are required for noise mapping (EU Directive), maximum noise levels are relevant for awakening and are often regulated at national or local level.

Environmental noise has a major impact on health, as described in the 2011 WHO report on health effects [WHO report Burden of disease environmental noise 2011]. Even those who do not state to be annoyed may still be health affected if highly exposed.
The numbers of people affected by road traffic noise are considerably higher than for railway noise. In the Venoliva study [@reference pending@] an estimates were made of numbers of people affected by road traffic noise as a function of proposed new vehicle noise limits. It was concluded that in 2010 around 90% of the EU27 population of 500 million is exposed (L_{DEN}>40 dB(A)) to road traffic noise. 119 million are annoyed, 55 million are highly annoyed. 60 million are estimated to be sleep disturbed and 27 million highly sleep disturbed. These figures seem consistent with noise mapping data collected by the EEA to date, which however is only based on noise mapping calculations of varying uncertainty.

For railways, numbers of people exposed, annoyed and sleep disturbed are estimated at a factor of around 5% of the figures for road traffic noise, so 23 million exposed, 6 million annoyed, 3 million highly annoyed, 3 million sleep disturbed and 1 million highly sleep disturbed.

3.2 Developments in noise legislation

There are several European directives dealing with noise legislation including noise mapping and action plans, en noise limits for road vehicles tyres and railway vehicles.

**Environmental Noise Directive**

In 2002, the Environmental Noise Directive (2002/49/EC) was adopted by the European Parliament and Council as a key means for tackling noise problems across the European Union. The Directive places a requirement on competent authorities in each Member State to produce noise maps for agglomerations and for major transport links including major roads, railways, and airports. This directive is under review and it is expected that the extent and quality of noise mapping will be increased. It should be noted that noise mapping is based on statutory calculation models and input data of varying quality including traffic intensity, vehicle types and speeds, road surface and others.

**Road vehicle noise limits**

Directive 70/157/EC [1] and its many subsequent amendments cover the requirements for motor vehicle exterior pass-by noise and the noise from the exhaust system under test conditions, covering the type testing method and noise limits. This directive is also under review and will probably include tighter noise limits for all types of road vehicle from 2013 or 2014.

**Tyre noise limits**

Directive 2001/43/EC proposed mandatory noise limits for tyres, which are expected to be tightened in 2012 and 2016. The initial limits were so high that most tyres passed, resulting in no reduction in environmental noise in the short term.

**Outdoor machinery noise limits**

Directive 2000/14 on the noise from outdoor equipment also includes a number of road vehicles with powered equipment on board including power sweepers, suction vehicles, refuse vehicles, mobile cranes and truck mixers. Although the noise levels are for operation of the equipment, some is powered from the vehicle engine and will therefore also affect powertrain noise during operation on the road. This directive is to be amended in 2011 probably introducing noise limits for some of these types.
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

EU Transport GHG: Routes to 2050?

Contract 070307/2010/579469/SER/C2

Railway vehicle noise limits
Noise limits for both conventional and high speed railway vehicles are regulated in EU directives 2002/735/EC (high speed) and 2006/66/EC (conventional rail including freight wagons). These cover noise during pass-by, acceleration and standstill.

Time to take effect on average noise levels
It should be noted that for all the above noise limit regulations, the impact in on real traffic noise levels takes as long as needed to replace the whole vehicle fleet or tyre population. Average road vehicle lifetime is about 12-13 years, and for tyres around 4 years. Railway vehicles can have a lifetime of up to 30 years and in some cases longer.

Baseline data for characteristic road types

Estimates for typical average traffic noise levels expressed as $L_{DEN}$ and $L_{NIGHT}$ in dB(A) at 15 m from the road are given for several different road types, as described in the Venoliva report. The road types each have characteristic traffic flows, speeds and vehicle types. The road types are:

- Residential road with intermittent traffic (e.g. near junction, crossing)
- Residential road with free flowing traffic
- Main road with intermittent traffic
- Main road with free traffic
- Arterial road
- Urban motorway
- Rural motorway
- Rural road.

These levels might be found on noise maps in urban areas.

Table 3: Baseline data for typical $L_{DEN}$ and $L_{NIGHT}$ noise levels for different road types.

<table>
<thead>
<tr>
<th></th>
<th>Resid int</th>
<th>Resid. free</th>
<th>Main int.</th>
<th>Main free</th>
<th>Arterial</th>
<th>Urban MW</th>
<th>Rural MW</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{DEN}$</td>
<td>54</td>
<td>52</td>
<td>67</td>
<td>65</td>
<td>74</td>
<td>72</td>
<td>74</td>
<td>55</td>
</tr>
<tr>
<td>$L_{NIGHT}$</td>
<td>46</td>
<td>43</td>
<td>57</td>
<td>55</td>
<td>65</td>
<td>63</td>
<td>65</td>
<td>46</td>
</tr>
</tbody>
</table>

3.3 Activity levels and modal shift

Activity levels for road and railway traffic are quantified primarily by traffic intensity (numbers per hour) of each vehicle type and their speeds. Noise pass-by levels of vehicles tend to depend on $30 \log_{10}$ of the vehicle speed, which implies a 9 dB increase when the speed is doubled. For a traffic flow the dependency of the average noise level $L_{DEN}$ can be less, $20 \log_{10}$ speed which corresponds to 6 dB per doubling of traffic speed.

For high speed trains, the speed dependency can be higher, up to $60 \log_{10}$ (speed) above 300 km/h.

The noise level from a traffic flow or intensity (number of vehicles per unit time) depends on $10 \log_{10}$ (intensity) and increases by 3 dB if the is doubled.

So the management of vehicle speed and numbers of vehicles are key parameters to control noise levels.
If we include management of traffic dynamics in the activity level, then the smooth flow of traffic and elimination of stop and go traffic is also important for noise control. Intermittent traffic tends to introduce extra noise due to acceleration and braking, which is less straightforward to predict.

The time of operation is crucial, as the $L_{DEN}$ quantity contains a higher weighting for evening and night time noise. As a consequence, shifting traffic to the night period can increase the average $L_{DEN}$ noise level. The resulting increase depends on the ratio between day/evening/night traffic and the vehicle types. For example, on busy motorways, if the proportion of trucks rises above 15% of all vehicles, they may dominate the overall noise level $L_{DEN}$ particularly due to the night contribution. For freight trains, similarly night time operation can determine the total $L_{DEN}$ level on a line with mixed traffic.

Traffic activity is mostly regulated at local level. In particular the access of (goods) vehicles to urban areas is often restricted in time, route or vehicle size, or subject to an environmental licence. This is an increasing trend as more and more inner cities seek to improve the quality of life in such areas both in terms of noise and of emissions.

There is also a clear trend to encourage modal shift of both goods and passengers away from the roads and onto public transport and rail, by means of congestion charging, infrastructure planning, facilitating walking, cycling and better access to urban centres.

Any such modal shifts tend to reduce the numbers of vehicles and thereby the noise levels and numbers of exposed people. The noise reductions are proportionate to the reduced traffic intensity.

An indication of a baseline of activity levels for road traffic can be given based on numbers of vehicles, typical annual mileage and growth trends. In the EU27 there is currently around 1 car per 2 persons, around 250 million cars with a growth rate in annual mileage of 1.6% (see Venoliva study [@reference pending@]). This can be interpreted as an expected increase in road traffic noise levels of 0.6 dB increase over 10 years, if no further measures are taken (such as new noise limits and others). The growth in vehicle kilometres is the dominant parameter compared with population growth. Noise from cars tends to be predominant above goods vehicles due to their large numbers.

Numbers of trucks and lorries are estimated at around 35 million in the EU27, with an annual mileage growth of 1.2%.

It is to be expected that in the future national and local authorities will continue to increase measures to limit the impact of this traffic growth by encouraging modal shift and regulating vehicle access and speeds in certain areas.

For the railways, several trends can be identified. Although for many years rail freight lost out to road transport, it recovered in recent years due to road congestion, new high speed and conventional rail connections and increased trade with eastern Europe. This trend will continue to increase due to policies to encourage modal shift to rail transport, for example the projected freight route to the Far East and new dedicated freight corridors. This is resulting in some increased complaints about noise from night time operations. Increased use of existing lines and construction of new high speed lines has lead to shifting of freight traffic and intensification on certain lines, for example the Rhein valley in Germany where passenger trains have shifted to the high speed line and numbers of freight trains have significantly increased, causing a major noise problem, primarily from rolling noise. Many rail freight routes still pass through urban areas at night time.

An important modal shift is the increased use of high speed connections between major cities instead of travelling by air. This results in an increased number of train movements.
However the increase in noise is only 3 dB per doubling of train numbers.

Noise reduction due to changing of activity levels can be large, from 2-10 dB or more if traffic intensity and speed is changed significantly. It can also take effect immediately when the measure is introduced.

### 3.4 Vehicle speed

As described above, road and railway noise depends strongly on speed, typically 20-30 \( \text{lg(speed)} \). Several trends are discussed here.

**Speed limits**

For roads, there is an increased trend to set speed limits also for limiting noise besides safety. Night time speed limits along urban motorways are a good example of this. This is much less the case for railways, with the exception of critical locations. For railways, speed limits for noise reduction are undesirable due to the effect on line capacity.

**Traffic flow**

Traffic flow control is a means of reducing noise from intermittent operation of vehicles both for roads and railways. For roads, green wave flow control is applied mainly to improve the traffic flow, also benefiting noise in some cases. For railways, avoiding braking and acceleration can save energy and also reduce locally high noise levels from brakes and the powertrain.

**Speed increase for railways**

There is a general and continuing trend towards increasing speed on the railways, in particular for passenger trains. Especially new high speed lines are critical in relation to noise. The opposite seems to be the case for road traffic, where average traffic speeds and speed limits tend in general to be lowering.

Noise level change due to changing speed will be between 1-3 dB for around 20% change traffic speed. It can also take effect immediately when the measure is introduced.

### 3.5 Road and Railway Track design and surface characteristics

The running surface of roads and rails are a main influence parameter for rolling noise excitation. Whilst both the surface of the wheel/tyre and of the road/rail both are relevant, high roughness levels on roads and rails can cause high noise levels. Good examples are cobbled roads, concrete slab roads with joints and corrugated or jointed rails.

The running surface quality can usually be improved resulting in significant noise reductions. For roads this involves replacement or resurfacing, for rails it generally involves rail grinding.

Road and railway authorities in a number of EU countries apply such measures to reduce noise emission, often as part of a noise action plan. It is to be expected that this solution will be applied more frequently in the future in noise critical situations.

Besides the surface quality, the design of the road and railways, in particular the track, have an effect on the emitted noise. For roads, the absorptive properties affect the road/tyre noise by several dB. For railways, the same is the case although absorption is already present on
ballast tracks. The stiffness of the railpad is another design parameter that affects the noise level – soft railpads tend to increase the vibration and resulting sound radiation of the rail.

Noise levels can be reduced by appropriate combination of surface quality, absorption, railpad stiffness and other parameters including screening, barriers, rail dampers.

It can be expected that noise control will become a more integral part of the design of both railways and roads in the future, especially now more advanced simulation models are available and legislation is stricter.

Improving the smoothness of rough road and rail surfaces may reduce noise levels by 3-6 dB depending on the initial condition of the road/track and the vehicle. It is most effective for situations with speeds above 50 km/h and takes immediate effect for vehicles with a smooth wheel/tyre surface.

### 3.6 Tyres and wheels

In the same manner as for roads and tracks, the running surface quality of tyres and wheels has a significant effect on rolling noise. This is taken into account in tyre design so as to comply with noise limits, avoiding periodic profiles if possible. For railway wheels, the quality of the running surface depends strongly on the braking system, in particular for tread brakes on the running surface. Cast iron brake blocks are still present on part of the freight fleet, causing up to 10 dB higher noise levels than disc or composite block brakes.

Tyre dimensions, materials, internal design and wear all affect the noise level besides rolling resistance (and energy consumption). Existing car tyres on the market vary in nominal noise emissions over a range of around 8 dB.

For railway wheels, the dimensions, cross-section design, and damping are also key parameters for noise emissions. Many current railway wheels are optimised in this respect. Both for tyres and railway wheels, simulation tools and testing methods are applied to optimise noise performance. Despite extensive research no recent technical breakthroughs have been achieved to reduce tyre noise by more than 10 dB.

Improving the smoothness of tyres and railway wheel surfaces may reduce noise levels by 1-10 dB depending on the initial condition. It is most effective for situations with speeds above 50 km/h and only achieves the full effect if all vehicles have similarly smooth wheels and that road/rails are also sufficiently smooth.

### 3.7 Vehicle propulsion

Vehicle propulsion is one of the main noise sources especially relevant in urban areas at lower speeds, for intermittent traffic and for larger vehicles such as lorries, trucks and buses. Whereas combustion engines are the common power source for both road and rail vehicles, electric traction which is widespread on the railways is increasingly applied on road vehicles. Its current and future breakthrough strongly depends on battery action range. For this reason also the hybrid powertrain is increasingly popular, mostly in road vehicles but also on some railways.

For goods vehicles, buses, locomotives and multiple units diesel engines are the preferred power source, whereas for cars, petrol and diesel engines are both popular. In the past, diesel engines were always noisier than petrol engines due to the higher compression ratio, but current diesel engines produce comparable noise levels to petrol engines.
For pass-by noise of cars and vans, engine noise may dominate tyre noise up to 30-50 km/h. For vehicle with larger engines such as lorries, busses, trucks, passenger trains and diesel locomotives engine noise may dominate up to 70-80 km/h.

If alternative fuels are used to power either a petrol engine or a diesel engine, the noise emission does not necessarily change as long as the fuel injection and ignition timing and compression remains the same. Alternative fuels are LPG, CNG, biofuels and hydrogen.

Electric powertrains and hydrogen fuel cells are generally much quieter than combustion engines, although tyre noise will still remain.

Hybrid powertrains, consisting of electric motors, combustion engine, generator and batteries have the same low noise emission of electric drives, except during the charging of the batteries. This typically occurs during a long drive or when extra power is required, for example during fast acceleration. Noise levels may be significant as the engine must deliver enough power on demand. Hybrid powertrains are increasingly popular for buses, goods vehicles and special vehicles with on board machinery, such as sweepers, refuse vehicles, aerial access platforms, and others. A main benefit in terms of noise is the possibility to charge the batteries during operation at normal road speeds when tyre noise is of a similar level. Hybrid powertrains have been applied for passenger trains which need to run both on and off the electrified network.

Due to environmental demand it can be expected that the use of electric and hybrid powertrains will increase in the coming years.

For combustion engines, noise levels are strongly engine speed dependent. Also the nominal power, engine size (cylinder volume) and design are influence factors for the noise level. Engine noise levels typically depend on engine speed as 30 lg (engine speed) and 10 lg (engine power).

There are a number of noise control options for combustion engines, including:

- damping of engine components
- (partial) shielding of engine components
- influencing electronic engine control parameters such as ignition time and speed;
- balancing;
- resilient mounting;
- intake and exhaust muffler design;
- design of cooling system.

There is no separate noise legislation for powertrains, it is always covered through noise limits for the whole vehicle. As noise limits for road vehicles will probably become tighter the vehicle fleet will gradually become quieter, which is possible using convention solutions as described above.

Changing or improving the vehicle propulsion system can be a highly effective measure to reduce traffic noise on roads with speeds up to 50 km/h and in intermittent traffic. It will only take effect slowly on the average traffic noise level as all vehicles must be modified or replaced, this will take up to about 12 years. The largest reductions can be achieved with electric and fuel cell powertrains, followed by hybrid powertrains and quieter conventional combustion engines.
4 Energy Security Co-benefits of GHG Reduction Policies

Objectives:
The purpose of this sub-task was to:

- **Develop a better understanding of the energy security co-benefits of GHG reduction policies, including:**
- **Build upon the initial energy security issue analysis undertaken in the ‘EU Transport GHG: Routes to 2050?’ study.**
- **As far as possible, undertake a full quantification of the energy security implications of potential transport sector abatement options.**

Summary of Main Findings
⇒ Work currently in progress. To be completed after the November Focus Group Meeting.

4.1 Introduction

This paper provides a quantitative assessment of the implications of transport-sector GHG abatement measures on energy security. The growing concern over climate change and sustainability will lead to radical changes in the structure of the transport energy system. A number of existing and proposed pathways to 2050 envision a far greater reliance on renewable supplies; however, to date, the interaction between achieving a sustainable transport system and improving energy security has not been assessed in detail.

In its Green Paper of 2006, the European Commission proposes a common policy to enable Europe to face the energy supply challenges of the future. The three core EU objectives to achieve this aim were identified as sustainability, competitiveness, and security of supply. With these objectives in mind, it is clear that energy security has played, and will continue to play, an important role in the development of future energy and climate policies.

There are many definitions of energy security, all of which include aspects that relate to the sufficient availability and reliability of energy supply. Most definitions also stress that the supply should be affordable. For instance, the International Energy Agency defined energy security as: “as adequate supply of energy at reasonable cost.”

Definitions now increasingly contain a sustainability dimension, which relates to climate change and other environmental impacts. This is because energy supplies that emit high levels of greenhouse gases are incompatible with a secure energy system in the long-term, given the need to mitigate the dangerous impacts of climate change. For example the European Commission (EC) Green Paper on security of energy supply stated: “Energy supply security must be geared to ensuring the proper functioning of the economy, the uninterrupted physical availability at a price which is affordable, while respecting environmental concerns”

For the purposes of this paper we have defined energy security as the availability of sufficient, affordable and sustainable energy supplies.

Sufficient supplies would constitute a large-scale fuel source that would not be limited by finite global stores. Although currently oil is sufficiently available on the international market,
there are concerns about future availability due to growing demand in non-OECD countries coupled with political instability in many of the oil-producing countries. Oil production has been widely predicted to peak at some point in the next decade. Sufficiency also relates to the susceptibility to shortfalls in production capacity and vulnerability to supply chain disruption. Affordable energy is crucial from an economic and social perspective. The high oil dependence of the transport sector is partially related to the low oil prices compared to alternative energy carriers over the past 20 years. Historically, low carbon fuel technologies have incurred a cost premium that makes energy less affordable; however, rising oil prices mean that conventional fuels are becoming more expensive. The concept of affordability is also related to minimising price volatility. In the case of oil, growing global demand, depletion of reserves and concentration of reserves in politically less stable regions all contribute to high uncertainty over price developments.

With respect to the transport sector, energy security is becoming an increasingly important issue, particularly given the current heavy reliance on oil-based fuels. Despite efforts to diversify supply, more than 96% of transport energy uses oil or oil products (EC, 2010). Uptake of biofuels has increased under the Biofuels Directive (2003/30/EC) and the Renewable Energy Directive (2009/28/EC), but effects on overall demand for hydrocarbon fuels have so far been minor. Thus, the supply of oil continues to be essential for maintaining a low-cost, uninterrupted and large-scale fuel supply.

4.1.1 Background to this paper

As part of the ‘EU Transport GHG: Routes to 2050?’ study, AEA carried out an initial analysis of energy security issues, which was presented in Report I “Energy security and the transport sector”\(^1\). This work included the following elements:

- An overview of energy security issues in the transport sector;
- A discussion of the extent to which the supply of energy for the transport sector is secure (qualitative assessment of the current and future situation);
- A review of existing approaches to quantify energy security benefits associated with GHG abatement options; and
- The development of a new framework for quantifying energy security benefits/impacts of transport sector GHG abatement options.

A key finding from the previous study was that existing analytical approaches were not sufficient for this purpose. Therefore we developed a framework based on multi-criteria analysis (MCA) that could be used to quantify where possible the impacts of transport sector abatement options on energy security. This can help decision-makers understand the synergies between climate policy and energy security.

Whilst the approach sets out a robust analytical framework, it was not possible to develop approaches for quantifying all of the relevant indicators in the previous study. This study builds on the previous work by:

- Providing quantitative rankings of policy options under the MCA framework;
- Extending the analysis to cover the timeframe from 2010 – 2050; and
- Using the quantitative rankings to assess the energy security implications of different policy options.

Our approach is set out in detail in the following section.

### 4.1.2 Approach

Our MCA framework takes into account the performance of each abatement option against a number of assessment criteria to produce an overall energy security score. The assessment criteria indicate the quality of each fuel in terms of energy security, which we have defined in this paper as supplies which are **sufficient, affordable and sustainable**. No single metric is able to adequately capture all of these factors, therefore a series of six factors have been defined which each cover one or more aspects. Together, these factors build up a rich picture of the different elements which constitute energy security. The assessment criteria are shown in Table 4.1.

**Table 4.1: Overview of energy security factors**

<table>
<thead>
<tr>
<th>Energy Security factor</th>
<th>Description</th>
<th>Energy security issues addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linkage to oil price</td>
<td>Oil price is forecast to increase and to become more volatile. We consider</td>
<td>Affordable</td>
</tr>
<tr>
<td></td>
<td>a close link with the price of oil to have a negative impact on energy security.</td>
<td></td>
</tr>
<tr>
<td>Proportion of current vehicle fleet</td>
<td>The effect of a measure on energy security depends on the impact of the</td>
<td>Sufficient</td>
</tr>
<tr>
<td>able to use the alternative fuel</td>
<td>measure in practice. One limiting factor is the capacity of existing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>vehicles to accommodate the measure. Closer to 2050 this becomes an</td>
<td></td>
</tr>
<tr>
<td></td>
<td>irrelevant factor given the lifetime of vehicles in the current fleet.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some vehicles may also be replaced before the end of their average</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lifetime as a result of the measure. It may therefore be appropriate to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>give this factor a low weighting in future assessments.</td>
<td></td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>High fuel costs are deemed to have a negative impact on energy security.</td>
<td>Affordable</td>
</tr>
<tr>
<td></td>
<td>The fuel costs are expressed as a ratio to the oil price.</td>
<td></td>
</tr>
<tr>
<td>Surplus supply capacity</td>
<td>Low surplus capacity is deemed to have a negative effect on energy</td>
<td>Sufficient</td>
</tr>
<tr>
<td></td>
<td>security.</td>
<td></td>
</tr>
<tr>
<td>Susceptibility to disruptions</td>
<td>The susceptibility of the alternative fuel source or measure to supply</td>
<td>Sufficient</td>
</tr>
<tr>
<td></td>
<td>disruption as a result of an extreme event (e.g. storm, civil unrest,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>political tension or terrorist attack) or market failures (e.g. inadequate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>investment in sufficient infrastructure or system overloading).</td>
<td></td>
</tr>
<tr>
<td>Resource concentration of energy</td>
<td>This factor reflects dependence on a relatively small number of suppliers</td>
<td>Affordable, sufficient</td>
</tr>
<tr>
<td>source</td>
<td>or supply routes</td>
<td></td>
</tr>
</tbody>
</table>

One of the key benefits of this approach is that both quantitative and qualitative data can be combined into a semi-quantitative ranking of the energy security benefits of different policy options. The policy options consider six broad fuel types as well as energy demand reduction. Today, oil derived fuels like gasoline and diesel (for road transport) are the dominant fuels, and natural gas plays a minor role. There is a small but increasing demand for biofuels, which are likely to be most important in the road sector, but could potentially have applications in aviation. Electricity is already used extensively in railways and is finding growing demand in road transport. Significant research and development is being carried out to investigate the potential for hydrogen as a potential substitute for conventional fossil fuels. The full MCA framework is shown in Figure 4.1.
A further major development to the framework in this study was to produce datasets for each factor over the full 2010-2050 period. This is critical, given that this study was focused on examining GHG abatement policies out to 2050. Technical developments and political objectives may result in substantial changes in the transport energy system. Values for each policy option were calculated for the years 2010, 2020, 2030, 2040, and 2050 based on forecasts for each energy source over the full time period. Where replacement fuels could be produced from a variety of processes and/or feedstocks, the effect of different methods has been taken into account. For example, biofuels can be produced from many different sources of biomass, broadly categorised as “first generation” (e.g. rape seed, corn, sugar cane) and “second generation” (agricultural or wood residues). Hydrogen can be produced from hydrocarbon feedstocks, biomass or electrolysis of water. The generation mix for electricity is also likely to change dramatically out to 2050, if Europe is to meet its GHG reduction targets.

Each alternative energy source has been assessed against the six energy security factors to determine the impact on energy security. The data has been sourced from existing literature, and extrapolated/interpolated where appropriate to cover the full timeframe. The methodology is explained in detail wherever these techniques have been used.

The advantage of this MCA framework is that it takes many factors into account to provide a high-level overview. This study involved an extensive literature review to gather the most recent and comprehensive reports, which were then aggregated within the MCA framework. These technical reports are typically characterised by a deep exploration of one factor. Therefore the MCA allows various tradeoffs to be taken into account. For example, an energy source may be relatively affordable and sustainable, but because it is vulnerable to supply disruptions it would not be considered sufficient. Examination of a broad range of criteria under the MCA ensures that the complex interplay between energy security factors is not missed. However, at the same time this may introduce further uncertainties into the results because the underlying assumptions and projections of these studies are necessarily varied. It is, however, the overall trends and broader picture which will be most telling.

The remainder of this section details the approach taken to establish the quantitative datasets for each of the factors under consideration.
4.2 Linkage between price of new energy source and oil price

Policy options

- Conventional oil derived fuels
- LPG
- Natural gas
- Biofuels
- Hydrogen
- Electricity
- Demand reduction

Factors

a) Linkage between price of new energy source and oil price
b) Proportion of vehicle fleet able to use new energy source
c) Cost of new energy source compared to oil
d) Surplus of supply capacity over demand
e) Susceptibility of new energy source to disruptions
f) Resource concentration for supply

4.2.1 Overview

The price of many alternative fuels is linked to the oil price and this could have an effect on energy security. This correlation arises when production and/or distribution of these fuels relies on conventional fossil fuels. The strength of this price relationship is key to assessing the energy security implications of alternative fuel sources in terms of sufficiency and affordability. If an alternative fuel relies to a large extent on oil for its production, this implies that it does not really represent a move away from oil-dependency and therefore it is less sustainable. Given that the oil price is expected to rise, a high reliance on oil for production also suggests that an alternative fuel will be less affordable. This indicator also provides a metric to assess volatility linked to fluctuations in the oil price – as oil price is forecast to increase and to become more volatile. We consider a close link with the price of oil to have a negative impact on energy security.

4.2.2 Assessment

In our previous research (AEA et al, 2010), we used estimates for this relationship from the EC’s Joint Research Centre, published in their Well-To-Wheels study (EC, 2006). These took the form of oil cost factors (OCF), which are ratios showing the effect of a percentage change in oil price on the price of the new energy source. For example, an OCF of 0.5 indicates that, for a given percentage change in oil price, the price will increase by 50% of the change for oil.

In this study we have developed individual OCF values for different resource feedstocks. We have also investigated likely changes in OCF values for other alternative fuels that could be used out to 2050. Technological developments may mean that alternative energy sources can be produced with lower reliance on fossil fuels, and thus the OCF values for some fuels may change.

In particular, we expect the changes in production pathways for biofuels, hydrogen and electricity to be significant. We have developed estimated OCF values for each of these fuels for the years 2010, 2020, 2030, 2040, and 2050 based on the likely production pathways for each alternative energy source over the full time period. The OCF for these fuels is assumed to reduce in line with decreasing reliance on fossil fuels for production, whereas the OCF for fossil fuels is assumed to remain unchanged.
This section therefore addresses the limitations of previous studies by:

- Developing more realistic, individual OCFs for different biofuel feedstocks;
- Developing OCFs for other alternative fuels that could be used in the future; and
- Investigating likely changes in the years 2020, 2030, 2040 and 2050.

### 4.2.3 Biofuels

The Well-To-Wheels study provided a single OCF value of 0.05 for biofuels produced from various resource feedstocks (wheat grain, sugar beet, rapeseed, etc). This value indicates that changes in biofuel prices are only weakly linked to changes in oil price, but it is well known that fossil fuels are used extensively in the production of biofuels (in cultivation processes, transport of feedstocks and fuels, drying of feedstocks, etc). Additionally, biofuels produced from different feedstocks rely on fossil fuels to varying extents, and hence different OCF values should be used.

#### Developing individual OCFs for 1st generation biofuels

The lifecycle GHG emissions of different biofuels provide an indication of the overall reliance on fossil fuels. Typical values have been developed for the Renewable Energy Directive (RED) (2009/28/EC). The GHG values consider emissions from: cultivation of raw materials; processing; transport and distribution.

#### Table 4.2: Typical GHG savings and OCF for biofuels if produced with no net carbon emissions from land use change

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Bioethanol - 1st generation production pathway</th>
<th>Typical GHG saving</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical GHG saving</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar beet ethanol</td>
<td>61%</td>
<td>0.507</td>
<td></td>
</tr>
<tr>
<td>Wheat ethanol (process fuel not specified)</td>
<td>32%</td>
<td>0.884</td>
<td></td>
</tr>
<tr>
<td>Wheat ethanol (lignite as process fuel in CHP plant)</td>
<td>32%</td>
<td>0.884</td>
<td></td>
</tr>
<tr>
<td>Wheat ethanol (natural gas as process fuel in conventional boiler)</td>
<td>45%</td>
<td>0.715</td>
<td></td>
</tr>
<tr>
<td>Wheat ethanol (natural gas as process fuel in CHP plant)</td>
<td>53%</td>
<td>0.611</td>
<td></td>
</tr>
<tr>
<td>Wheat ethanol (straw as process fuel in CHP plant)</td>
<td>69%</td>
<td>0.403</td>
<td></td>
</tr>
<tr>
<td>Corn (maize) ethanol, Community produced</td>
<td>56%</td>
<td>0.572</td>
<td></td>
</tr>
<tr>
<td>Sugar cane ethanol</td>
<td>71%</td>
<td>0.377</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biodiesel - 1st generation production pathway</th>
<th>Typical GHG saving</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rape seed biodiesel</td>
<td>45%</td>
<td>0.715</td>
</tr>
<tr>
<td>Sunflower biodiesel</td>
<td>58%</td>
<td>0.546</td>
</tr>
<tr>
<td>Soybean biodiesel</td>
<td>40%</td>
<td>0.780</td>
</tr>
<tr>
<td>Palm oil biodiesel (process not specified)</td>
<td>36%</td>
<td>0.832</td>
</tr>
<tr>
<td>Palm oil biodiesel (process with methane capture at oil mill)</td>
<td>62%</td>
<td>0.494</td>
</tr>
</tbody>
</table>

Source: EC (2009) and study team calculations
Notes: The typical GHG saving is compared to the average emissions from the fossil part of petrol and diesel consumed in Europe, which is assumed to be 83.8gCO2-e/MJ (Directive 2009/28/EC)20. The biofuel GHG calculation methodology provides two sets of values: “typical” values are the central figures from the range of values for each biofuel pathway. “Default” values have a 40% mark-up on the “typical” values to reflect the wide variation in emissions. It is the “typical” values which have been used here, as the “default” values are intended to provide a safety margin for calculations made under Directive 2009/28/EC.
The OCF for each biofuel has been developed by weighting the OCF for gasoline and diesel by the typical GHG saving for each biofuel\(^{21}\). This gives figures which are significantly higher than the 0.05 OCF suggested in the EC’s Joint Research Centre WTW study (EC, 2006), but which are more in line with the (estimated) value of 0.5 used in Report I “Energy security and the transport sector”.

### Developing OCFs for 2\(^{nd}\) generation biofuels

Typical values for the lifecycle GHG savings of future biofuels have been developed for the Renewable Energy Directive (RED) (2009/28/EC). “Future” biofuels are those that were not on the market or were on the market only in negligible quantities in January 2008. The GHG emissions consider emissions from: extraction or cultivation of raw materials; processing; transport and distribution; in-use emissions and carbon capture.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Bioethanol - 2(^{nd}) generation production pathway</th>
<th>Typical GHG saving</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw ethanol</td>
<td>87%</td>
<td>0.169</td>
<td></td>
</tr>
<tr>
<td>Waste wood ethanol</td>
<td>80%</td>
<td>0.260</td>
<td></td>
</tr>
<tr>
<td>Farmed wood ethanol</td>
<td>76%</td>
<td>0.312</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Biodiesel - 2(^{nd}) generation production pathway</th>
<th>Typical GHG saving</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste wood Fischer-Tropsch diesel</td>
<td>95%</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>Farmed wood Fischer-Tropsch diesel</td>
<td>93%</td>
<td>0.091</td>
<td></td>
</tr>
</tbody>
</table>

Source: EC (2009) and study team calculations

Again, the OCF for each biofuel has been developed by weighting the OCF for gasoline and diesel by the typical GHG saving for each fuel. Note that the OCFs for these new alternative fuels tend to be much lower than for known biofuels due to their lower dependence on fossil fuels during production.

Aggregate OCFs could be calculated for bioethanol and biodiesel by taking a weighted average across the production technologies. For the purposes of this report, the proportion of production coming from various feedstocks was based on analysis of the European biofuel market in 2020 by DG Agriculture (European Commission, 2007). The actual OCF will vary greatly depending on the mix of production technologies; however, this approach was used as an illustrative example only. The input data are summarised in Table 4.4.

### Table 4.3: Estimated typical GHG and OCF for future biofuels, if produced with no net carbon emissions from land use change

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Mio t</th>
<th>% of total</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st}) generation bioethanol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar beet</td>
<td>2.34</td>
<td>4%</td>
<td>0.507</td>
</tr>
<tr>
<td>Wheat</td>
<td>43.06</td>
<td>72%</td>
<td>0.884</td>
</tr>
<tr>
<td>Maize</td>
<td>14.18</td>
<td>24%</td>
<td>0.572</td>
</tr>
<tr>
<td>1(^{st}) generation biodiesel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapseseed</td>
<td>28.32</td>
<td>71%</td>
<td>0.715</td>
</tr>
<tr>
<td>Sunflower seed</td>
<td>1.77</td>
<td>4%</td>
<td>0.546</td>
</tr>
<tr>
<td>Soybean seed</td>
<td>9.25</td>
<td>23%</td>
<td>0.780</td>
</tr>
<tr>
<td>Palm oil</td>
<td>0.36</td>
<td>1%</td>
<td>0.832</td>
</tr>
</tbody>
</table>

Source: European Commission (2007)

Aggregate OCFs for 2\(^{nd}\) generation biofuels were not needed, as most 2\(^{nd}\) generation biofuels are expected to be produced from farmed wood (European Commission, 2007).

---

\(^{21}\) Uses OCF for diesel and gasoline of 1.3
Table 4.5: Aggregate OCFs for 1st and 2nd generation biofuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Assumed feedstock</th>
<th>Overall OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st generation</td>
<td>See Table 4.4</td>
<td>0.795</td>
</tr>
<tr>
<td>2nd generation</td>
<td>Farmed wood</td>
<td>0.312</td>
</tr>
</tbody>
</table>

Bioethanol

| 1st generation | See Table 4.4 | 0.724 |
| 2nd generation | Farmed wood   | 0.091 |

Biodiesel

<table>
<thead>
<tr>
<th>Typical GHG saving</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st generation</td>
<td>0.724</td>
</tr>
<tr>
<td>2nd generation</td>
<td>0.091</td>
</tr>
</tbody>
</table>

Final OCFs were calculated by weighting the OCF for first and second generation biofuels. The weighting factors from 2010-2030 were obtained from ECN (2008) and assumed to remain constant for the remainder of the period.

Table 4.6: OCF for biofuels

<table>
<thead>
<tr>
<th>% 1st generation biofuel</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>83%</td>
<td>0.71</td>
<td>0.56</td>
<td>0.49</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>17%</td>
<td>0.62</td>
<td>0.42</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
</tbody>
</table>

% 2nd generation biofuel

<table>
<thead>
<tr>
<th>% 2nd generation biofuel</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>48%</td>
<td>0.71</td>
<td>0.56</td>
<td>0.49</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>63%</td>
<td>0.62</td>
<td>0.42</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Source: EC (2009), ECN (2008) and study team calculations

Notes: OCF for 1st and 2nd generation biofuels is assumed to remain constant. Percentage of 1st and 2nd generation biofuels is assumed to apply to both bioethanol and biodiesel. Calculated OCF will vary significantly depending on the assumptions made for the likely feedstocks and/or production processes – the numbers shown here are for illustrative purposes only.

4.2.4 Hydrogen

The EC provides projections for hydrogen production by technology to 2050 (EC, 2006). The reference case has been used to refine the OCF estimates out to 2050 in this study. There are also two other scenarios in addition to the reference case which assume higher percentages of hydrogen production from renewable sources. The reference scenario has been used as it represents the most conservative case.

Figure 4.2: Fossil fuel dependency of H₂ production

Source: EC (2006) and study team calculations

Notes: Assumed 100% fossil fuel dependency in 2010; assumed hydrogen production from unspecified processes is fossil fuel dependent.
Table 4.7 shows the fossil fuel dependency of hydrogen production is expected to decrease with time. The reference case from EC (2006) assumes that the most widespread hydrogen production process will be steam reforming of natural gas in the short-term. Other potential production pathways include: partial oxidation of coal; pyrolysis of biomass; high-temperature thermolysis using solar/nuclear; water electrolysis. After 2020 production is anticipated to be mostly from non-fossil fuels, particularly renewable sources and nuclear.

Table 4.7: OCF for hydrogen

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>% fossil fuel dependency</td>
<td>100%</td>
<td>50%</td>
<td>29%</td>
<td>20%</td>
<td>12%</td>
</tr>
<tr>
<td>OCF</td>
<td>0.8</td>
<td>0.40</td>
<td>0.23</td>
<td>0.16</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Source: EC (2009) and study team calculations

Notes: Values for 2040 obtained using linear interpolation; assumed 100% fossil fuel dependency in 2010; assumed hydrogen production from unspecified processes is fossil fuel dependent.

4.2.5 Electricity

The Eurelectric study (2010) provides projections for the electricity generation mix by source fuel to 2050. The reference case has been used to refine the OCF estimates out to 2050 in this study as it represents the most conservative case for energy production from renewable sources. The fuel split is shown in Figure 4.3.

Figure 4.3: Fossil fuel dependency of electricity generation

Source: Eurelectric (2010)

Notes: Reference case projections used

The reference scenario predicts a gradual reduction in contributions from oil, gas and solid fuel (coal) – with carbon capture and storage. The large role of nuclear may be less realistic following the recent troubles in Japan. At the time of writing, revised estimates were not available. We would expect the fossil fuel dependency to make up the shortfall from nuclear generation, as renewable energy plant is likely to be more expensive (power generation
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

EU Transport GHG: Routes to 2050?

Contract 070307/2010/579469/SER/C2

investment under the higher renewable energy scenario in the Eurelectric report is predicted to be €162 billion greater between 2025 and 2050. Table 4.8 shows the decreasing fossil fuel dependency in the reference case and the OCFs subsequently calculated from the given values.

Table 4.8: OCF for electricity

<table>
<thead>
<tr>
<th>% fossil fuel dependency</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCF</td>
<td>0.5</td>
<td>0.43</td>
<td>0.18</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Source: Eurelectric (2010) and study team calculations
Notes: Values for 2040 obtained using linear interpolation; fossil fuel dependency includes generation from oil, natural gas and solid fuel.

4.2.6 Overall OCFs

The projected OCFs have been recast on a scale of 0-100, where a higher score represents a lower OCF, and hence a higher energy security for this factor.

Table 4.9: Normalised OCFs on a scale of 0-100

<table>
<thead>
<tr>
<th>Fuel</th>
<th>OCF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Conventional oil-derived fuels (e.g. gasoline/diesel)</td>
<td>0</td>
</tr>
<tr>
<td>LPG</td>
<td>8</td>
</tr>
<tr>
<td>Natural gas</td>
<td>41</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>45</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>57</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>41</td>
</tr>
<tr>
<td>Electricity</td>
<td>66</td>
</tr>
<tr>
<td>Energy demand reduction</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: AEA et al. (2010) and study team calculations
Notes: A high score indicates high energy security. Scores for bioethanol and biodiesel are illustrative only. OCFs for fossil fuels (gasoline/diesel, LPG, natural gas) and energy demand reduction are assumed to remain constant. OCF for biofuels have been kept stable for all fuels after 2030. OCF taken for bioethanol and biodiesel assumes the proportion of 1st generation biofuel is 83% in 2010, 52% in 2020 and 37% in 2030-2050 (the average of the two scenarios in ECN, 2008). The remainder of demand is met by 2nd generation biofuels. OCF for bioethanol & biodiesel (1st & 2nd generation) takes the unweighted average of OCFs calculated in section 4.2.3
Under the assumptions used (see section 4.2.3), biofuels score well compared to fossil fuels. This score improves as the proportion of second generation biofuels grows. However, it is very important to note that the scores for bioethanol and biodiesel are *illustrative only*, and could change depending on the assumed mix of production processes. Production from hydrogen is also predicted to have a low reliance on oil for production in the future, where renewable sources and nuclear will become more important. The score for electricity gradually improves over the time period as the grid decarbonises. Energy demand reduction does not involve a change in fuel type, hence it takes the same OCF as gasoline/diesel.
4.3 Proportion of vehicle fleet able to use new energy source

<table>
<thead>
<tr>
<th>Policy options</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Conventional oil derived fuels</td>
<td>a) Linkage between price of new energy source and oil price</td>
</tr>
<tr>
<td>• LPG</td>
<td>b) Proportion of vehicle fleet able to use new energy source</td>
</tr>
<tr>
<td>• Natural gas</td>
<td>c) Cost of new energy source compared to oil</td>
</tr>
<tr>
<td>• Biofuels</td>
<td>d) Surplus of supply capacity over demand</td>
</tr>
<tr>
<td>• Hydrogen</td>
<td>e) Susceptibility of new energy source to disruptions</td>
</tr>
<tr>
<td>• Electricity</td>
<td>f) Resource concentration for supply</td>
</tr>
<tr>
<td>• Demand reduction</td>
<td></td>
</tr>
</tbody>
</table>

4.3.1 Overview

Energy security could be enhanced by diversifying the fuel sources used by the transport sector. The impact of a given measure on energy security would be limited by the capacity of existing vehicles to accommodate the measure. Thus, the number of vehicles which are able to use an alternative energy source sets an upper limit on the ability of a fuel to support the transport system. Whilst alternative energy sources can reduce dependence on oil, if vehicles are not capable of using these alternative fuels, then overall energy security would not be improved. Therefore, this factor provides an indication of sufficiency, in terms of demand-side constraints. The availability of such vehicles depends on the realistic rate of their deployment and the rate at which incompatible vehicles are withdrawn from the fleet. Figure 4.5 shows the factors which dictate the proportion of the vehicle fleet which is compatible with alternative fuel.

Figure 4.5: Proportion of vehicle fleet able to use alternative fuels

- Rate of technological development
- Policy frameworks which support development
- Deployment of alternative fuel vehicles
- Rate of withdrawal of incompatible vehicles
- Proportion of vehicle fleet able to use alternative fuel

The rate of deployment of alternative fuel vehicles is influenced in turn by the rate of technological development and the existence of a policy framework to support uptake of these fuel types.
4.3.2 Assessment of overall fleet

The varying lifetimes of different vehicle types must be taken into account. For example, passenger cars tend to have average lifetimes of 10-12 years, meaning that the fleet turns over relatively quickly. By contrast, railway rolling stock, ships, and aircraft have much longer lifetimes (30-40 years), meaning that the take-up of alternative energy sources may be more limited unless fuels that are compatible with existing engines are used.

A quantified estimate of potential EU future fleet capabilities to use various alternative energy sources is to be sourced primarily based on data from the SULTAN model developed as part of this project. For each potential alternative energy source, estimates of the proportion of the total EU vehicle fleet able to use this energy source are proposed to be developed based on the activity in vehicle-km weighted relative to estimates of the average gross vehicle weight of different modes, in order to normalise for significant differences in vehicle sizes between modes. This metric is currently still under development and will be implemented following the Focus Group meetings in November 2011, following feedback.

4.4 Cost of new energy source compared to oil

Policy options

- Conventional oil derived fuels
- LPG
- Natural gas
- Biofuels
- Hydrogen
- Electricity
- Demand reduction

Factors

- a) Linkage between price of new energy source and oil price
- b) Proportion of vehicle fleet able to use new energy source
- c) Cost of new energy source compared to oil
- d) Surplus of supply capacity over demand
- e) Susceptibility of new energy source to disruptions
- f) Resource concentration for supply

4.4.1 Overview

A key element of energy security is affordability, which is assessed in this indicator. With rising energy costs, affordable prices have become a central element of energy security concerns.

4.4.2 Price projections

Price projections for all fuels in terms of €/MJ (excluding taxes) have been obtained from the latest SULTAN baseline scenario, as shown in Table 4.10.

Table 4.10: Price of fuels (€/MJ)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>0.014</td>
<td>0.017</td>
<td>0.021</td>
<td>0.023</td>
<td>0.025</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.015</td>
<td>0.018</td>
<td>0.021</td>
<td>0.024</td>
<td>0.026</td>
</tr>
<tr>
<td>LPG</td>
<td>0.020</td>
<td>0.024</td>
<td>0.029</td>
<td>0.032</td>
<td>0.035</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.011</td>
<td>0.021</td>
<td>0.026</td>
<td>0.029</td>
<td>0.033</td>
</tr>
<tr>
<td>Biofuel</td>
<td>0.025</td>
<td>0.023</td>
<td>0.022</td>
<td>0.021</td>
<td>0.020</td>
</tr>
</tbody>
</table>
The projected prices of fuels were then recast on a scale of 0-100, where a higher score represents lower price, and hence a higher energy security for this factor.

Table 4.11: Normalised price of fuels on a scale of 0-100

<table>
<thead>
<tr>
<th>Fuel</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>90</td>
<td>84</td>
<td>77</td>
<td>73</td>
<td>69</td>
</tr>
<tr>
<td>Diesel</td>
<td>88</td>
<td>82</td>
<td>75</td>
<td>71</td>
<td>67</td>
</tr>
<tr>
<td>LPG</td>
<td>78</td>
<td>70</td>
<td>60</td>
<td>55</td>
<td>49</td>
</tr>
<tr>
<td>Natural gas</td>
<td>95</td>
<td>76</td>
<td>67</td>
<td>61</td>
<td>53</td>
</tr>
<tr>
<td>Biofuel</td>
<td>68</td>
<td>72</td>
<td>74</td>
<td>77</td>
<td>78</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>41</td>
<td>26</td>
<td>7</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Electricity</td>
<td>55</td>
<td>39</td>
<td>37</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
<td>Jet fuel</td>
<td>97</td>
<td>93</td>
<td>88</td>
<td>85</td>
<td>82</td>
</tr>
<tr>
<td>Ship fuel</td>
<td>100</td>
<td>86</td>
<td>80</td>
<td>77</td>
<td>73</td>
</tr>
</tbody>
</table>

For the price factor, it appears that gasoline, diesel, LPG and CNG are the cheapest fuels in the short term. This highlights the general situation where renewable and low-carbon fuels currently tend to cost more than the fossil fuels we currently rely on. Overall, hydrogen and electricity are the options with the highest cost. In the case of hydrogen, the price increases...
because it is currently produced from natural gas, but over time larger amounts are expected to come from electrolysis. Cost estimates for future biofuels are difficult to make, particularly for second generation production processes which are still under development. Current biofuel costs are to a large extent dependent on the feedstock prices – 55% to 70% of total production costs, according to the IEA Bioenergy (2008). Feedstock costs for second generation biofuels are expected to be lower, in part as they tend to arise as waste or residue streams, or from non-food energy crops but also because the capital costs for the production plants are significantly higher. Other factors affecting cost include government subsidies, changes in the oil price, shortages and overproduction.

It should be noted that the €/MJ metric may not, on its own, be sufficient as a means of carrying out comparisons. This is because the cost of energy to end-users is driven not only by the price paid per unit of energy received, but also by the overall energy efficiency of the technology using the particular energy source. For example, vehicles powered by electricity (either directly via grid electricity or indirectly via hydrogen fuel cells) are significantly more efficient than those powered by internal combustion engines. The majority (up to 80-90%) of the electrical energy provided to an electric vehicle will be used to provide motive power, whereas much of the energy contained within fossil fuels such as petrol and diesel is lost as heat in the combustion process (a typical passenger car diesel engine is between 25% and 30% efficient). This factor means that the energy consumption per vehicle kilometre travelled can be very different for the various possible energy sources; the implication of this is that it is possible for the unit energy price of an energy source to be high, but for the costs per vehicle kilometre travelled to be lower than for vehicles powered by energy sources with low unit energy prices.

Therefore, in order to account for this different efficiency in the use of different energy carriers it will be necessary to either:

(a) Compensate for different relative efficiencies within the energy cost factor; OR
(b) Potentially add an additional energy security factor that specifically deals with this aspect;

This could potentially be achieve via the energy consumption per gross tonne-km for vehicles utilising different energy carriers, derived from vehicle efficiency per km (e.g. from SULTAN) normalised to average vehicle weight for a metric comparable across different modes.

A decision on the approach to be adopted will be made and implemented following feedback from the Focus Group meetings in November 2011.

4.5 Surplus of supply capacity over demand

Policy options
- Conventional oil derived fuels
- LPG
- Natural gas
- Biofuels
- Hydrogen
- Electricity
- Demand reduction

Factors
- a) Linkage between price of new energy source and oil price
- b) Proportion of vehicle fleet able to use new energy source
- c) Cost of new energy source compared to oil
- d) Surplus of supply capacity over demand
- e) Susceptibility of new energy source to disruptions
- f) Resource concentration for supply
4.5.1 Overview

This indicator provides an assessment of sufficiency. We analyse the global capacity/stores of each fuel compared to expected demand. A sufficient fuel would constitute a large-scale source that would not be limited by finite global stores.

Current rates of oil production are sufficient, but capacity must increase to meet the demand growth expected over the coming decades. This depends on the remaining reserves of oil and the capacity of oil companies to increase the rate of extraction.

World oil reserves are notoriously difficult to establish and estimates of the global ultimate recoverable reserves range from under 1,000 billion barrels to over 4,000 billion barrels. Many believe that oil production will peak in the next decade as discoveries of new oil fields decline and oil from established fields becomes progressively more difficult and expensive to extract. There are also doubts over the ability of the oil industry to invest sufficiently to boost production levels to meet demand. The IEA has estimated that $4.3 trillion of investment would be needed between 2005 and 2030. It is thought likely that these difficulties in investing to boost production capacity are more imminent than shortages due to a depletion of resources. Some commentators have noted that the high oil prices experienced in 2007 and 2008 were due to limitations in production capacity as Saudi Arabia, the world’s largest oil producer was not able to increase production to help stabilise prices, implying that there was limited, or no spare capacity. Shortfalls in production capacity are likely to lead to high levels of price volatility, with corresponding negative economic impacts. Furthermore, high levels of oil price volatility may lead to an uncertain investment climate for alternative renewable energy technologies.

4.5.2 Assessment

This metric is currently still under development and will be implemented following the Focus Group meetings in November 2011, following feedback.

4.6 Susceptibility of new energy source to supply disruptions

<table>
<thead>
<tr>
<th>Factors</th>
<th>Policy options</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Linkage between price of new energy source and oil price</td>
<td>• Conventional oil derived fuels</td>
</tr>
<tr>
<td>b) Proportion of vehicle fleet able to use new energy source</td>
<td>• LPG</td>
</tr>
<tr>
<td>c) Cost of new energy source compared to oil</td>
<td>• Natural gas</td>
</tr>
<tr>
<td>d) Surplus of supply capacity over demand</td>
<td>• Biofuels</td>
</tr>
<tr>
<td>e) Susceptibility of new energy source to disruptions</td>
<td>• Hydrogen</td>
</tr>
<tr>
<td>f) Resource concentration for supply</td>
<td>• Electricity</td>
</tr>
<tr>
<td></td>
<td>• Demand reduction</td>
</tr>
</tbody>
</table>
4.6.1 Overview

The susceptibility of an energy source to supply disruption is an indicator of **sufficiency**. The changes in energy sources required to meet 2050 GHG reduction targets would require a significant level of additional investment compared to a business-as-usual scenario. Several issues may prevent sufficient investments being made including:

- Lack of certainty regarding policy interventions;
- Lack of financing available for the scale of investment required;
- Uncertainty associated with impact of changing capacity mix;
- Administrative barriers such as securing planning permission; and
- Changes to revenue streams caused by e.g. price caps affect the price signals, introduction of intermittent generation leading to periods of low or negative prices.

Furthermore, extreme weather events can disrupt both supply and demand. Supply side effects include disruption of energy infrastructure or supply chains. Demand side impacts can be caused by significant increases in demand, e.g. due to exceptionally hot or cold spells. The consequent disruption will typically depend on the level of market concentration or – in the case of demand-side impacts – the effect on peak demand and supply shortfall. The overall severity of the disruption depends on other system factors such as supply flexibility, storage capacity, and distribution and transmission infrastructure.

The number of worldwide weather catastrophes has shown an increasing trend since the 1950s, with greater numbers of storms, floods, and mass movement, as well as increasingly frequent episodes of extreme temperature, drought and forest fires (NatCatSERVICE, 2011).

Figure 4.7: Worldwide weather catastrophes, 1950-2010

![Figure 4.7: Worldwide weather catastrophes, 1950-2010](image)

Source: NatCatSERVICE, 2011

Some renewable energy sources would be affected by weather conditions; for example, solar and wind production would cease during severe storms. In the future this impact should be limited because new energy systems are designed to accommodate fluctuations in renewable supply. In general, increased renewable supply with improve energy security because of greater distributed generation. Biofuel production could be vulnerable to extreme
weather events, particularly where the EU relies on imports of palm oil from drought- or typhoon-prone regions. However, the wide geographical distribution of biofuel should limit this impact.

4.6.2 Assessment

In our previous study, we developed a semi-quantitative scale for assessing the susceptibility of each policy option to supply disruptions. These are summarised in Table 4.12, where a higher score means the policy option has a higher resilience to supply disruption.

Table 4.12: MCA score for susceptibility of energy source to disruptions

<table>
<thead>
<tr>
<th>Policy option</th>
<th>MCA score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional oil-derived fuels (e.g. gasoline/diesel)</td>
<td>50</td>
</tr>
<tr>
<td>LPG</td>
<td>50</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0</td>
</tr>
<tr>
<td>Biofuels</td>
<td>50</td>
</tr>
<tr>
<td>Hydrogen fuel cell</td>
<td>0</td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
</tr>
<tr>
<td>Energy demand reduction</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: AEA (2010)

The MCA score was developed using professional judgement in the previous study, as it is very difficult to quantify this parameter. In this section, we have further extended the analysis by providing qualitative rankings out to 2050.

The scores have been sourced from the World Energy Council (2007), where expert members of the Mobility Specialist Study Group provided “availability” rankings for each fuel. The availability refers to reliability and security of energy supply systems, once access has been achieved i.e. the quality and reliability of service. The scores have been taken for OECD countries.

Table 4.13: WEC scores for accessibility and availability of fuels

<table>
<thead>
<tr>
<th>Policy option</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional oil-derived fuels (e.g. gasoline/diesel)</td>
<td>4.2</td>
<td>4.0</td>
<td>3.6</td>
<td>3.0</td>
</tr>
<tr>
<td>LPG</td>
<td>4.1</td>
<td>4.2</td>
<td>4.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Natural gas</td>
<td>3.8</td>
<td>3.7</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>3.6</td>
<td>3.5</td>
<td>3.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>3.1</td>
<td>2.9</td>
<td>2.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Hydrogen fuel cell</td>
<td>1.3</td>
<td>1.8</td>
<td>2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Electricity</td>
<td>1.8</td>
<td>2.4</td>
<td>3.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Energy demand reduction</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Source: WEC (2007) and study team analysis

Notes: Scores were taken for OECD countries. Scores have been calculated as an average of the marks given for accessibility and availability. Scores for 2030 and 2040 have been calculated by linear interpolation between 2020 and 2035, and 2035 and 2050. Gasoline/diesel scores are the average of the scores for gasoline spark ignition and diesel compression ignition engines. Electricity is assumed to correspond to the OECD mix in Enerdata.

The scores were then recast on a scale of 0-100, where a higher score represents a lower probability of supply disruption, and hence a higher energy security for this factor. Scores for 2010 were taken from our previous study (AEA, 2010), whereas scores for 2020-2050 were taken from the World Energy Council report (2007).
Table 4.14: Normalised scores for susceptibility of energy source to supply disruptions on a scale of 0-100

<table>
<thead>
<tr>
<th>Policy option</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional oil-derived fuels (e.g. gasoline/diesel)</td>
<td>50</td>
<td>77</td>
<td>76</td>
<td>68</td>
<td>51</td>
</tr>
<tr>
<td>LPG</td>
<td>50</td>
<td>49</td>
<td>43</td>
<td>38</td>
<td>32</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0</td>
<td>49</td>
<td>43</td>
<td>38</td>
<td>32</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>50</td>
<td>68</td>
<td>66</td>
<td>62</td>
<td>57</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>50</td>
<td>62</td>
<td>60</td>
<td>56</td>
<td>49</td>
</tr>
<tr>
<td>Hydrogen fuel cell</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>29</td>
<td>49</td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>14</td>
<td>30</td>
<td>50</td>
<td>73</td>
</tr>
<tr>
<td>Energy demand reduction</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: AEA (2010), WEC (2007) and study team analysis

Figure 4.8: Normalised score for susceptibility of new energy source to supply disruption

The figures provided here represent the consensus view of experts, however we stress again that it is very difficult to quantify the susceptibility of an energy source to supply disruptions. The results show that gasoline and diesel become more susceptible to supply disruptions in the short-medium term, but this risk drops again by 2050. This is likely due to assumptions that synthetic fuel from coal (coal-to-liquids) will also be produced in large industrial scale after 2035. First generation biofuels are gradually replaced by second generation biofuels, which improve the score in the short-medium term, but the long-term outlook is less certain. Hydrogen supply may be impaired by a limited infrastructure at first, but supply is expected to gradually grow from renewable sources. Energy demand reduction takes the highest score throughout the time period, as it would not depend on external supply factors to implement.
4.7 Resource concentration for the supply of the new energy resource

<table>
<thead>
<tr>
<th>Policy options</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Conventional oil derived fuels</td>
<td>a) Linkage between price of new energy source and oil price</td>
</tr>
<tr>
<td>• LPG</td>
<td>b) Proportion of vehicle fleet able to use new energy source</td>
</tr>
<tr>
<td>• Natural gas</td>
<td>c) Cost of new energy source compared to oil</td>
</tr>
<tr>
<td>• Biofuels</td>
<td>d) Surplus of supply capacity over demand</td>
</tr>
<tr>
<td>• Hydrogen</td>
<td>e) Susceptibility of new energy source to disruptions</td>
</tr>
<tr>
<td>• Electricity</td>
<td></td>
</tr>
<tr>
<td>• Demand reduction</td>
<td>f) Resource concentration for supply</td>
</tr>
</tbody>
</table>

4.7.1 Overview

The uneven global distribution of fossil fuel reserves is a pertinent cause of energy insecurity. The Organization for the Petroleum Exporting Countries contains around 75% of proven reserves, while OECD countries only account for 7% (IEA, 2007). Over 50% of proven gas reserves are found in three countries: Russia, Iran and Qatar. This geographical concentration of resources endows regions with a certain amount of market power which could adversely affect energy security in terms of affordability and sufficiency.

A high concentration of resources suggests that exporters have greater market power, which could affect the affordability of the fuel. Conversely, a smaller concentration of resources suggests that the market will be more competitive. This will also help to improve sufficiency, because local disruptions to the supply chain will not affect all producers.

4.7.2 Fossil fuels

Depletion of fossil fuel reserves is a key driver of long-term energy security concerns. However, it is the resulting resource concentration, rather than the level of reserves per se, which is the root of the problem. Without resource concentration, depletion would be gradual and price increases would stimulate the market to develop alternative energy sources.

Europe imports oil from a small number of countries, indicating that there is a significant issue with resource concentration.

The IEA (2007) has calculated a measure of market concentration in terms of Energy Security Market Concentration (EMSC). The ESMC indicator is based on the well-established Herfindhal-Hirschman Index (HHI) which measures market concentration by taking into account the number of suppliers in a particular market, and their respective market shares. The ESMC is the sum of the square of the individual market shares of all the countries which produce the fuel. The market share of fuel is defined by its net export capacity, which reflects the total level of exports a country can physically place on the market. For each fuel, ESMC is defined by:

\[ EMSC = \sum_i S_i^2 \]
Where $S_i$ is the share of each supplier $i$ in the market of fuel $f$, defined by its net export potential (from 0-100%).

Values of ESMC vary from 0 to 10,000, where a higher ESMC value implies lower energy security. A score of 0 represents a perfectly competitive market, whereas a score of 10,000 represents a pure monopoly.

Table 4.15: ESMC of fossil fuels

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil market</td>
<td>3420</td>
<td>4040</td>
<td>4810</td>
<td>5580</td>
<td>6350</td>
</tr>
<tr>
<td>Gas market</td>
<td>970</td>
<td>1050</td>
<td>890</td>
<td>850</td>
<td>810</td>
</tr>
<tr>
<td>Coal market</td>
<td>1954</td>
<td>2112</td>
<td>2270</td>
<td>2428</td>
<td>2586</td>
</tr>
</tbody>
</table>

Source: IEA (2007) and study team analysis
Notes: OPEC countries considered as a single supplier; assume no change in gas price structure in Europe, values for 2040 and 2050 have been approximated using extrapolation.

Oil-derived fuels (gasoline, diesel, LPG) are assumed to take the same ESMC as oil. Gas-derived fuels (CNG) are assumed to follow the gas market ESMC.

4.7.3 Biofuels

The measure of ESMC is based on a measure of net export potential of countries. Global biofuel production by region was sourced from BP’s outlook to 2030 (BP, 2010). It shows that biofuel production is expected to increase strongly in North, South and Central America. Production in Europe and the Asia Pacific also increases significantly, whereas the Middle East and Africa do not increase production.

Table 4.16: Biofuel production by region (Mtoe)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>28</td>
<td>39</td>
<td>49</td>
<td>72</td>
<td>97</td>
</tr>
<tr>
<td>S &amp; C America</td>
<td>19</td>
<td>31</td>
<td>51</td>
<td>65</td>
<td>78</td>
</tr>
<tr>
<td>Europe &amp; Eurasia</td>
<td>7</td>
<td>13</td>
<td>19</td>
<td>19</td>
<td>29</td>
</tr>
<tr>
<td>Middle East</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Africa</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>4</td>
<td>10</td>
<td>14</td>
<td>23</td>
<td>30</td>
</tr>
</tbody>
</table>

Source: BP (2010)

Global biofuel consumption by region was sourced from the IEA’s World Energy Outlook (2009). Consumption is expected to more than double in North, South and Central America and Europe. In the Asia Pacific, consumption is predicted to increase fourfold.

Table 4.17: Biofuel consumption by region (Mtoe)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>20</td>
<td>29</td>
<td>42</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>S &amp; C America</td>
<td>12</td>
<td>16</td>
<td>18</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>Europe &amp; Eurasia</td>
<td>13</td>
<td>20</td>
<td>26</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td>Middle East</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Africa</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>5</td>
<td>11</td>
<td>17</td>
<td>23</td>
<td>31</td>
</tr>
</tbody>
</table>

Source: IEA WEO (2009)

The net export potential of a country is assumed to be the difference between total production and consumption (IEA, 2007):

\[
\text{Net exports} = \text{total production} - \text{total consumption}
\]
And the EMSC is defined by:

$$\text{EMSC} = \sum_i S_i^2$$

Where $S_i$ is the share of each supplier $i$ in the market of biofuels, defined by its net export potential. Countries with negative export potentials were assigned a value of 0. For this calculation, we have used regions instead of countries, as sufficiently granular data were not available.

Table 4.18: EMSC of biofuels

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofuels</td>
<td>2,170</td>
<td>4,380</td>
<td>7,180</td>
<td>7,953</td>
<td>8,454</td>
</tr>
</tbody>
</table>

Source: BP (2010), IEA WEO (2009) and study team calculations
Notes: Values for 2040 and 2050 have been approximated using extrapolation.

The EMSC rises throughout the period, primarily due to increased production in North, South and Central America. The high scores, particularly from 2030-2050 are likely to be due to the calculation methodology, which assigned net export capacity values to global regions as opposed to countries (as was assumed for the other fuel types).

4.7.4 Hydrogen and Electricity

We have calculated approximate values for the ESMC of hydrogen and electricity by assuming the production methods develop in line with the reference scenario detailed in EC (2006). The ESMC of oil, gas and coal is weighted according to the percentage of production each fossil fuel accounts for.

Contributions from renewable sources are assumed to have an ESMC value of zero. This is because while resource concentration is clearly a problem for fossil fuels, renewable energy sources have not traditionally been subject to analysis because they tend to be developed through national markets. When suppliers are defined as countries, as they are in this study, a purely national market clearly has no export potential, and therefore the ESMC is zero. We note, however, that renewable energy sources are unevenly distributed; for example wind, solar and geothermal resources vary between regions. Also, in the future it may be preferable to import hydrogen and electricity produced from low-cost renewable sources in neighbouring countries. The transportation costs will increase total costs, however, so domestic production is likely to be preferred where possible. If, in the long-term, renewable sources are no longer exploited purely within domestic boundaries, ESMC may become an issue. Analysis of these impacts may be warranted in further work.

The values obtained by this weighted analysis are summarised in Table 4.19, where it can be seen that the ESMC generally decreases over time as renewable sources make greater contributions. There is an increase in the ESMC for hydrogen at 2030 because production from steam reforming of natural gas is limited by high prices, therefore coal takes a higher share until more renewable sources become available after 2030.

Table 4.19: ESMC of hydrogen and electricity

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>773</td>
<td>864</td>
<td>817</td>
<td>738</td>
<td>690</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>970</td>
<td>842</td>
<td>904</td>
<td>230</td>
<td>120</td>
</tr>
</tbody>
</table>

Source: EC (2006); IEA (2007) & study team analysis

The effects of importing hydrogen and/or electricity from countries outside of Europe have not been taken into account, because the contributions are expected to be small. Hydrogen corridors based on fossil fuel or nuclear feedstocks are not beneficial as it is usually more
efficient to transport the feedstock itself due to the low volumetric density of hydrogen (Wietschel & Hasenauer, 2007\textsuperscript{22}). Long-distance hydrogen transport may lead to cost increase of 17-65%. In a review of the need for electricity corridors, electricity trades are estimated to be between 100 TWh to 180 TWh (10 Mtoe – 15 Mtoe). This represents 2-4% of electricity demand in the EU27 in 2030, or 1-2% of demand in the 44 countries included in the study (EC, 2007\textsuperscript{23}). Although this is a large increase compared to the current situation, it is only a small proportion of overall demand; therefore effects of electricity imports have been ignored in the current analysis.

4.7.5 Overall EMSC

The projected EMSCs were then recast on a scale of 0-100, where a higher score represents a lower EMSC, and hence a higher energy security for this factor.

Table 4.20: Normalised EMSCs on a scale of 0-100

<table>
<thead>
<tr>
<th>Fuel</th>
<th>EMSC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Conventional oil-derived fuels (e.g. gasoline/diesel)</td>
<td>60</td>
</tr>
<tr>
<td>LPG</td>
<td>60</td>
</tr>
<tr>
<td>Natural gas</td>
<td>89</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>74</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>74</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>89</td>
</tr>
<tr>
<td>Electricity</td>
<td>91</td>
</tr>
<tr>
<td>Energy demand reduction</td>
<td>100</td>
</tr>
</tbody>
</table>

\textsuperscript{22} Wietschel & Hasenauer (2007) Feasibility of hydrogen corridors in the EU and its neighbouring countries

\textsuperscript{23} EC (2007) Energy corridors: European Union and neighbouring countries
The EMSC for all fuels has been estimated in 2040 and 2050 by extrapolating the trends seen between 2010 and 2030. Biofuels clearly show the lowest scores for this indicator in the long term, indicating that resources are highly concentrated in North, South and Central America. The high scores compared to other energy sources is likely to be due to the calculation methodology, which assigned net export capacity values to global regions as opposed to countries (as was assumed for the other fuel types). This was due to a lack of sufficient data in this area. Hydrogen and electricity perform particularly well on this metric, due to the expected large contributions from renewable energy sources. Natural gas also shows a high score, due to the large number of suppliers.

4.8 Energy security implications of different GHG emissions abatement options

Work is currently in progress on this element, to be finalised after feedback from the Focus Group meetings in November 2011.

A quantitative assessment is being developed based on the same basic assessment framework developed in the previous study, updated with the new datasets developed as part of this project work. This will produce percentage energy security indicators for each abatement option based on a multi-criteria analysis (MCA) using all the normalised scores.

The initial proposal is for this MCA to be based on an unweighted average of each factor (to be tested with the participants of the Focus Group meeting in November 2011), so that a single overall score will be assigned to each fuel. The changes over time would then be...
mapped graphically. This assessment will be complemented by further visual comparisons, such as star graphs, with an illustrative example provided in Figure 4.10.

**Figure 4.10:** Illustrative example of a potential visual comparison of the relative performance of different energy security factors

### 4.9 References


BP (2011) Outlook to 2030. [http://www.bp.com/sectiongenericarticle800.do?categoryId=9037134&contentId=7068677](http://www.bp.com/sectiongenericarticle800.do?categoryId=9037134&contentId=7068677)


UIC Sustainability Conference (2010) Railways: Mobility for a sustainable future


5 Health Co-benefits of GHG Reduction Policies

Objectives:
The purpose of this sub-task was to develop a better understanding of the health benefits of GHG reduction policies, including:

- The number and severity of traffic accidents (e.g. through speed reduction policies);
- Physical exercise carried out by the population in general due to a shift to non-motorised transport modes (cycling and walking).

Summary of Main Findings

⇒ A reduction in speed is likely to result in lower accident risks and less severe accidents;
⇒ Based on theoretical considerations, it is expected that road charging schemes result in an improvement of traffic safety;
⇒ Where CO₂ emission standards lead to the reduction in the average mass of vehicles, it is likely that a lower severity of accidents will result;
⇒ Introduction of hybrid/electric cars (on a large scale) in the fleet may result in a higher accident rate as vehicles may not be audibly detectible by pedestrians and cyclists; and
⇒ Modal shift from car to bike will probably result in an increase in the total number of fatalities and injuries. However, the shift from car to public transport will, in most cases, result in a slight improvement of traffic safety.
⇒ Physical inactivity leads to a number of different health effects, including chronic heart disease, type 2 diabetes, cancer and obesity. Physical inactivity can therefore lead to higher healthcare costs and lower productivity.
⇒ When more ‘active’ transport modes are introduced, more people tend to walk and cycle.
⇒ It is possible to quantify and monetise the health benefits gained by increased physical activity: Increased physical activity from cycling can lead to a €0.30 to around €1.20 per/km health benefit.
⇒ Indicative estimates for the EU range from 9 to 37 billion euro/year, in the case that 10% of the inactive people would become active due to increased walking and cycling. Where this is increased to a third, the benefits could range from 31 to 122 billion euro/year.
⇒ The health effects of increased physical activity therefore represent significant financial benefits and therefore should also be taken into account when assessing the cost-effectiveness of transport and climate policies

5.1 Assessment and quantification of health impacts of GHG reduction policies

As indicated in the introduction to this paper, GHG reduction policies for the transport sector can have various co-benefits on health in different areas (i.e. air quality, noise, accidents and physical exercise). For each of these effects, two mechanisms can be distinguished. The first one is the way GHG policy for transport induces these effects. The second is the impact

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24 Reduced climate change itself can also have various health benefits. However, since these are related to the primary aim of climate policy, these should not be labelled as co-benefits.
these effects have on human health. In order to understand the health impacts of these policies, both mechanisms should be assessed.

The impacts of GHG policies on improved air quality and reduced ambient noise are already covered in the other subtasks of Task 1. This subtask focuses on the health impacts from accidents and physical exercise:

- Reductions in the number and/or severity of traffic accidents (e.g. through speed reduction policies);
- Increases in the amount of physical exercise carried out by the population in general due to a shift to non-motorised transport modes (cycling and walking); and

The health impacts of the various GHG reduction policies has been assessed in this chapter and, where possible, quantified by analysing:

- The way GHG policy for transport induces these effects; and
- Impacts of these effects on human health.

The health impacts of reductions in the number and severity of accidents has been based on data on the:

- Shift to modes with lower accident rates or less severe accidents;
- Reduction of overall transport volume; and
- Lower accidents risks within transport modes, e.g. because of intelligent transport systems, lower vehicle mass and lower traffic speeds.

The health benefits associated with increased levels of physical exercise amongst the population due to a shift to non-motorised transport modes (cycling and walking) has been based on a brief literature review on the main types and order of magnitude of health benefits that can be expected.

An overview of the type and size of potential health benefits from impacts on traffic accidents and from increased amounts of physical exercise due to modal shift has been provided at the end of this chapter.

## 5.2 Health impacts of reductions in number/severity of accidents

Traffic accidents are one of the main adverse impacts of transport, in particular for road transport. In 2008, approximately 40,000 people were killed in road traffic accidents in Europe (European Commission, 2010) and another 280,000 people were seriously injured (ETSC, 2010). Rail traffic accidents were responsible for 144 fatalities and 543 serious injuries in 2008 in the EU (UIC, 2008). Finally, the number of fatalities in plane crashes on European territory was in 2008 equal to 17125 (Eurostat, 2011).

Greenhouse gas reduction policies in transport may have important impacts on the traffic safety in Europe. These impacts may be positive as well as negative. In this chapter we will assess for a selection of GHG reduction policies the impact on traffic accidents. In section 5.2.1 we first discuss some of the most important drivers of traffic accidents. This analysis will be the starting point for the discussion on the impact of some GHG reduction policies on the number and severity of traffic accidents in section 5.2.2. The assessment has been

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25 Due to a large plane crash in Spain the number of fatalities in 2008 was rather high. For comparison, in 2007 the number of fatalities were equal to 79 (Eurostat, 2011). Data on the number of injuries due to plane crashes were not available.
focused on GHG reduction policies which are expected to have the most significant impacts on traffic accidents: speed limits, road charging, vehicle standards and policy instruments stimulating modal shift to slow modes and public transport. The conclusions of this chapter are presented in section 5.2.3.

5.2.1 Drivers of traffic accidents

The number and severity of traffic accidents is influenced by many factors. In this section we discuss the most important ones: speed, traffic volumes, vehicle characteristics, infrastructure characteristics, drivers characteristics and external factors (e.g. weather conditions).

5.2.1.1 Speed

One of the most important drivers of traffic accidents is (traffic) speed. A higher speed increases the likelihood of an accident as well as the severity of the accident.

**Speed and accident risks**

The increasing accident risk by higher speed is caused by the fact that drivers have less time to react and prevent an accident. Additionally, the braking distance of vehicles increases with higher speed levels. The relationship between speed and accident risk has been studied extensively. One of the most influential results in this research area is provided by Nilsson (1982). He found that the relationship between speed and accidents can be described as a power function: the accident risk increases faster when the speed increases (see Figure 5.1).

*Figure 5.1: The exponential relation between speed and accident risk*

![Exponential relation between speed and accident risk](source: SWOV (2009))

The exponential relation between speed and accident risk is stronger for fatalities and severe injuries than for slight injuries. This can be illustrated by the core formula of Nilsson’s Power Model:

\[ A_2 = A_1 \left( \frac{V_2}{V_1} \right)^\beta \]

with \( A_2 \) being the number of accidents after the change in speed, \( A_1 \) being the initial number of accidents, \( V_1 \) and \( V_2 \) being the initial and new average speed levels respectively, and \( \beta \) the so-called power factor. For fatal accidents \( \beta \) is equal to 4, while for accidents involving both fatal and serious injuries this power factor is equal to 3. Finally, a power factor of 2 applies to all injury accidents. This power function for the relationship between speed and the number of accidents is validated by several studies (e.g. Elvik et al., 2004; Nilsson, 2004). Based on the Power Model of Nilsson, Aarts and Van Schagen (2006) have calculated the effect of speed changes for different initial speed levels and for different accident severities (see Table 5.1).
Table 5.1: The expected effect of a speed change of 1 km/h on the number of accidents of different severities at different initial speeds

<table>
<thead>
<tr>
<th>Accident severity</th>
<th>Initial speed</th>
<th>50 km/h</th>
<th>70 km/h</th>
<th>80 km/h</th>
<th>90 km/h</th>
<th>100 km/h</th>
<th>120 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury accidents</td>
<td></td>
<td>4.0%</td>
<td>2.9%</td>
<td>2.5%</td>
<td>2.2%</td>
<td>2.0%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Severe injury</td>
<td></td>
<td>6.1%</td>
<td>4.3%</td>
<td>3.8%</td>
<td>3.4%</td>
<td>3.0%</td>
<td>2.5%</td>
</tr>
<tr>
<td>accidents</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatal accidents</td>
<td></td>
<td>8.2%</td>
<td>5.9%</td>
<td>5.1%</td>
<td>4.5%</td>
<td>4.1%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

Source: Aarts and Van Schagen (2006)

The relationship between speed and accident risk differs between road types. According to SWOV (2009) accident risks increase less rapidly on motorways than on lower order roads by increasing speed levels. This could (very probably) be explained by differences in complexity of the road and traffic environment. Rural and especially urban roads have much more complex traffic situations than motorways and combined with the limited abilities of people to cope with large quantities of information, this results in higher accident risks by increased speed levels, compared to motorways.

Next to absolute speeds, also speed differences between vehicles have an impact on accident risks. Roads with a large speed variance are less safe (Aarts and Van Schagen, 2006). Therefore, policy instruments resulting in a lower average speed, but simultaneously in bigger speed differences, may in the end even result in higher accident risks, while policies that reduce speed differences will generally result in lower accident rates.

**Speed and accident severities**

The relationship between speed and the severity of accidents is less complicated than the relationship between speed and accident risks. At a higher speed, more energy is released when colliding with another vehicle, road user or obstacle, and hence more serious consequences will result. Although vehicles have become better equipped (with crush areas, airbags and seatbelts) to absorb the energy released in a crash, the collision speed is still very important for the crash outcome. At a collision speed of 80 km/h, the possibility of a fatal accident is about twenty times higher than at a speed of 30 km/h (SWOV, 2009).

**5.2.1.1.2 Traffic volumes**

As traffic volumes increase on a road the speed goes down and – as mentioned above – this negatively impacts the probability on an accident. However, an increase in the total number of vehicle kilometres will have a positive relationship with the total number of accidents. According to UNITE (2002) all empirical evidence available shows that the second effect is bigger than the first one, and hence the number of road traffic accidents increases as traffic volumes increase. This conclusion is confirmed by Duivenvoorden (2010).

However, will the number of accidents increase in proportion to the increase in traffic volume, or will the increase be progressive or degressive? This relationship between accidents and traffic levels can be expressed by so-called risk elasticities (GRACE, 2006). The elasticity will be positive in case of a progressive relationship between traffic volume and number of accidents. This means that an additional user increase the risk for an accident for all other users. If the number of accidents per kilometre increases in proportion to the traffic volume, the elasticity is zero (an additional user has no impact on the accident risk of other users). Finally, if the accident risk decreases with increasing traffic volume, the elasticity will be negative.

The relationship between traffic volumes and accident risks is investigated by several studies. Reviews of these studies are performed by Duivenvoorden (2010), GRACE (2006) and the High Level Group (1999). The latter study concludes that the number of accidents
Development of a better understanding of the scale co-benefits associated with transport sector GHG reduction policies

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rises proportionally with traffic volumes for normal traffic levels in inter urban areas and more than proportionally for higher levels of traffic and in urban areas. Duivenvoorden (2010) finds for secondary roads that the accident risk decreases by increasing traffic volumes. However, she mentions that this conclusion should be seen as a preliminary conclusion instead of a hard fact due to the limited amount of research on this issue. Although GRACE (2006) mentions some studies which present results comparable with the High Level Group (1999) and/or Duivenvoorden (2010), it concludes based on a review of a rather large number of studies that there is no consensus on the relationship between traffic volumes and accident risks.

Next to the relationship between the number of accidents and traffic volumes, the High Level Group (1999) also studied how the severity of accidents may vary with traffic flows. It was indicated that at high traffic flows drivers may concentrate more and drive at lower speeds. This is likely to result in fewer sever accidents.

5.2.1.1.3 Vehicle characteristics

There are substantial differences in the crashworthiness of different car models. The mass and the size of the car are essential factors in explaining these differences. Big car models have a lower occupancy risk while they are more aggressive, i.e. generates more casualties for non-occupants than smaller cars.

For overall traffic safety especially differences in mass between vehicles are important. These mass differences determine which vehicle absorbs which part of the released energy. Generally speaking, the energy absorption is inversely proportional to the mass of the vehicles. Mass differences between vehicle types can be large, e.g. the mass of a lorry may be up to 50 times higher than the mass of a passenger car. However, there are also considerable mass differences between cars (up to a factor 4); these differences have increased over the years (as is illustrated for the Netherlands in Figure 5.2) and are expected to become even larger in the coming years. This ‘incompatibility’ of vehicles is a main cause of fatality and injury risks of travel movements.

Figure 5.2: Distribution of vehicle mass in 2000 and 2010 in the Dutch passenger car fleet

Source: CBS (2011), adapted by CE Delft
Berends (2009) investigated for the Netherlands the relationship between mass differences of passenger cars and the fatality and injury risk in car-car collisions. In this study an exponential relationship between these factors are found. For example, a driver of a passenger car of about 800 kg that collides with a car of average mass (about 1,079 kg) has double the fatality rate of a driver of an average mass car who collides with that same vehicle. On the other hand, the risk that the light vehicle causes fatal injury to the opposing driver is only half the average fatality rate. For a driver of a car of 2,100 kg these rates are five and a fifth times the rate of those of the driver of a car of average mass. The differences in rates for injury risks are smaller, since these rates are less dependent on the relative mass difference.

Between slow modes (cyclists and pedestrians) and motor vehicles the incompatibility is of a completely different order. For example, the mass difference between a cyclist or pedestrian and a 50 tonnes lorry is ca. a factor 700. In addition, cyclists and pedestrians (but also moped riders and motorcyclists) are not protected by an ‘iron cage’, which could absorb some of the energy released in a collision.

5.2.1.1.4 Infrastructure

Accident risks also depend on the type of infrastructure. In general, urban roads have the highest accident risks, followed by interurban roads and motorways (Wijnen and Houwing, 2006). However, also within road categories large differences in accident risks could exist. Aarts and Van Schagen (2006) found that the total accident risk on interurban roads is higher on roads with a greater junction density and on narrow roads. These factors enlarge the complexity of driving on the infrastructure and hence accident risks increase. Finally, also the condition of the infrastructure matters. HGL (1999) note that the accident risks on an old road construction may be three times higher than on a modern motorway. The same relationship between infrastructure quality and accident risk was found for rail: e.g. on high quality tracks the fatality risk is 30% lower than on an average track.

5.2.1.1.5 Other drivers

Next to the drivers discussed above, accident risks and severity are also influenced by some other factors, like characteristics of the driver and weather conditions. According to the literature, accident risks are dependent on driver behaviour and personality. Age, for example, has a significant impact on the risk of causing an accident; young drivers (< 25 years) have an accident risk between two and six times higher than middle age drivers, while the accident risk of old people may be six to nine times higher than for the middle age group. Also personality characteristics, like control, aggressiveness or lifestyle influence accidents risks, although they can not explain more than 10 to 20% of the accident variation (HGL, 1999). Alcohol consumption is also an important driver of accident risks, e.g. a alcohol consumption of 1.5 increases the risk by a factor forty.

Traffic safety also depends on the weather conditions. Various studies (e.g. Bijleveld and Churchill, 2009; Keay & Simmonds, 2005) show that accident risks increase by a factor two by rainy weather, which is caused by a deterioration of the visibility and of the road holding of the car. The impact of other weather conditions on accident risks is more limited, but there is some empirical evidence (for an overview see SWOV, 2009) that accident risks increase due to:

- **fog**: due to poor visibility and shorter following distances to other traffic participants since people drive somewhat slower

- **low sun**: poor visibility

- **wind**: high vehicles can be pushed or can even be rolled over
• **icing**: increased risk on slipperiness; and
• **heat**: people are more irritable to others, get tired, lose their concentration, get their reaction time slower, etc.

### 5.2.2 Impacts on traffic accidents of various instruments

In this section we investigate the impact on traffic accidents of a selection of GHG policy instruments. This assessment is mostly based on ex-ante and ex-post evaluation studies of implemented or intended policy instruments.

#### 5.2.2.1 Speed limits

As we saw in section 5.2.1.1 limiting the speed of vehicles will reduce the risk on and severity of accidents. Reducing speed limits may therefore result in improved traffic safety. Additionally, reducing speed limits may lead to smaller speed differences on roads, which will also improve traffic safety. Finally, the relative impact of reducing speed limits on traffic safety will be higher for motorways than for urban roads (due to the exponential relationship between accident risks and initial speed levels). However, due to the higher initial accident risks on urban roads, the absolute impacts may be higher on urban roads than on motorways.

Since speed is also an important driver of transport volumes (AEA et al., 2010), reducing speed limits will generally - on the long term - also result in lower transport volumes. As we saw in section 5.2.1.2, these lower transport volumes will also have a positive impact on the traffic safety.

The positive impact of reducing speed limits on traffic safety is confirmed by empirical evidence from several studies. For example, Scholz et al. (2007) reports that the introduction of a speed limit of 130 km/h on some specific German motorways resulted in a 48% reduction of accidents. The number of fatalities decreased by even 57%.

Also Van Beek et al. (2008) reports decreasing accident risks as a result of stricter speed limits. The introduction of an 80 km/h zone on a Dutch motorway between The Hague and Rotterdam (initial speed limit 100 km/h) results in 50% less injury accidents. A strict enforcement by section control was in place. Enlarging of the number of 80 km/h zones resulted in significant safety improvements, in line with the Nilsson power-rule. However, the effects differ widely between the various locations, due to differences in local traffic dynamics.

TML (2009) studied the safety impacts of lowering the speed limits for passenger cars on Belgian motorways to 100 or 110 km/h (current speed limit: 120 km/h). Based on an adapted version of the power model of Nilsson, they estimated the impacts on accident risks and number of victims. The main results of their research are summarized in Error! Reference source not found.. As may be expected, the largest decrease was shown for the number of fatalities, followed by the number of severe injuries.
Table 5.2: Safety impacts of a lowering of speed limits on Belgian motorways (current limit 120 km/h)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Speed limit 100 km/h</th>
<th>Speed limit 110 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in number of accidents</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidents with fatalities</td>
<td>-38%</td>
<td>-18%</td>
</tr>
<tr>
<td>Accidents with severe injuries</td>
<td>-23%</td>
<td>-11%</td>
</tr>
<tr>
<td>Accidents with slight injuries</td>
<td>-13%</td>
<td>-6%</td>
</tr>
<tr>
<td>Accidents with only material damages</td>
<td>-12%</td>
<td>-5%</td>
</tr>
<tr>
<td>Change in number of victims</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatalities</td>
<td>-44%</td>
<td>-22%</td>
</tr>
<tr>
<td>Severe injuries</td>
<td>-27%</td>
<td>-12%</td>
</tr>
<tr>
<td>Slight injuries</td>
<td>-18%</td>
<td>-8%</td>
</tr>
</tbody>
</table>

Source: TML (2009)

5.2.2.1.2 Road charging

Road charging schemes may affect traffic safety in various ways:

- Lower transport volumes may result in a decrease in accident risks (see section 5.2.1.1.2). The lower transport volumes are the result of a decrease in road transport demand and/or a modal shift to other transport modes (e.g. train).

- A shift to other modes (e.g. public transport, cycling) may also affect accident risks and safety. As we saw in section 5.2.1.1.3 this depends on the risk and aggressiveness profile of the respective modes.

- Depending on the way the road charging scheme is designed, there may be changes in the composition of the vehicle fleet which have traffic safety implications. For example, a road pricing scheme differentiated to vehicle weight will result in a lower average weight of the average car and hence lower relative mass differences between cars; the latter may result in lower fatality and injury risks, as discussed in section 5.2.1.1.3.

- A road pricing scheme differentiated to time (i.e. congestion charge) may result in a spread of traffic over the day, which result in lower transport volumes on specific roads on specific times. This may eventually result in lower accident risks.

Evaluation studies (ex-ante and ex-post) on existing and intended road pricing schemes show contrary results. In the Netherlands extensive ex-ante research on the impacts of a national road pricing scheme shows an improved traffic safety due to road charging. Basic principle of the scheme studied was a variabilisation of the fixed vehicle taxes (e.g. purchase taxes, registration taxes), which would result in an average kilometre charge for passenger cars of ca. 6.5 €cent and 1.3 €cent for trucks. The 15% decrease in the total number of vehicle kilometres resulting from the implementation of the kilometre charge, would lead to ca. 7% less fatalities and injuries (Schemers and Reurings, 2009).

An ex-post evaluation study of the London congestion charge shows no clear conclusions on the impacts on traffic safety (TfL, 2007). The evaluation study shows that the number of personal injury accidents in the charging zone decreases at a higher rate than the number of personal injury accidents in the rest of London (see Table 5.3). However, based on the figures reported no acceleration in the decreasing accident rates due to the congestion charge could be identified (the congestion charge was introduced in 2003). This is not in line...
with the theory described in section 5.2.1.1.2, which predicts that the number of accidents decrease when transport volumes reduce. Notice that the figures in Table 5.3 refer only to personal injury accidents and do not include accidents with only material damages; so it could be possible that the latter type of accidents have decreased after the introduction of the congestion charge and hence it may even be possible that the total number of accidents have decreased. However, no information is available to test this hypothesis.

Table 5.3: Total reported personal injury road traffic accidents in London

<table>
<thead>
<tr>
<th></th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of personal injury accidents</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charging zone</td>
<td>1644</td>
<td>1418</td>
<td>1270</td>
<td>1131</td>
<td>1001</td>
<td>925</td>
</tr>
<tr>
<td>Rest of London</td>
<td>18410</td>
<td>16964</td>
<td>16226</td>
<td>14695</td>
<td>13782</td>
<td>12554</td>
</tr>
<tr>
<td><strong>Relative change in personal injury accidents (compared to previous year)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charging zone</td>
<td>14%</td>
<td>10%</td>
<td>11%</td>
<td>11%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Rest of London</td>
<td>8%</td>
<td>4%</td>
<td>9%</td>
<td>6%</td>
<td>9%</td>
<td></td>
</tr>
</tbody>
</table>

Source: TfL (2007)

In Figure 5.3 the development of accident severity in the charging zone is shown. Again, no clear deviation from the autonomous decreasing trend can be identified.

Figure 5.3: Reported personal injury road traffic accidents within the charging zone and inner Ring Road per severity class

Finally, an evaluation study on the congestion charge in Stockholm did not provide evidence on the impact of the congestion charge on traffic safety (Stockholmsförsöket, 2006). Due to the short period covered by the study, no significant effects of the congestion charge on road traffic accidents could be established.

To conclude: based on theoretical considerations a road charging scheme may be expected to result in an improvement of traffic safety. This was confirmed by the ex-ante evaluation study of a road charging scheme of all roads in the Netherlands. No empirical evidence was found for a significant impact of urban congestion schemes on traffic safety, although this may be due to limitations in the evaluation studies available.
5.2.2.1.3 Vehicle standards

The introduction and tightening of emissions standards for vehicles may result in various changes of vehicle characteristics. The two main ones with regard to traffic safety are the reduction in average mass of vehicles and the (large-scale) introduction of hybrid/electric cars in the vehicle fleet.

CO₂ emission standards for vehicles may lead to a reduction in the average mass of these vehicles (due to downsizing or the use of lightweight materials). Since cars still have to comply crash safety standards, this mass reduction will not have significant impact on the safety of individual cars. However, there may be an impact on the overall traffic safety. The reduction in average vehicle mass may – on the long term - result in a reduction of the mass differences in the vehicle fleet and hence a reduction in the average accident severity (see section 5.2.1.1.3). To realize the full long term improvement potential in traffic safety, it is important that the CO₂ emission standards hold for both passenger cars and vans/trucks. If this is not the case, mass differences between these vehicles are enlarged and consequently also the severity of accidents involving these modes.

With regard to hybrid/electric cars, there are concerns about potentially higher accident risks of these vehicles due to their low noise levels (CE Delft et al., 2011). Electric and hybrid vehicles may not be audibly detectable by pedestrians (especially visually impaired) and cyclists. The problem can be especially acute at urban intersections with loud background noise. In response to the ‘silent’ vehicle issue there were several recent studies performed to better understand the issue and a number of technical solutions were proposed. Based on these studies CE Delft et al. (2011) identify the following three categories of technical solutions:

- Infrastructure-based; examples include intersection rumble strips and audio warnings at intersections.
- Communications-based, which include personal proximity warning transmitters, electronic travel aids.
- Vehicle-based, which include artificial vehicle sounds when approaching intersections or moving at low speeds.

It is concluded that there are an adequate number of low cost solutions to address the problem of silent vehicles and that regulatory bodies are expected to propose specific industry-wide solutions to this issue in the near future.

5.2.2.1.4 Policy instruments stimulating modal shift to slow modes and public transport

Recent studies on the safety impacts of a modal shift from the car to cycling show an increase in the total number of fatalities and injuries due to this shift (Stipdonk & Reurings, 2010; Van Kempen et al., 2010). The exchange between short-distance car trips and cycling is only beneficial for young (especially male) drivers; they have a rather high accident risk profile when driving a car and are, in contrast to older people, less vulnerable with regard to bicycle accidents. These recent results on the safety impacts of exchanging car trips by cycling trips are not supported by older studies, like AVV (2005), CE Delft (2001) and Jensen et al. (2000). In these studies, increased cycling appears to be linked to an overall reduction in road crash rates, which could be (partly) explained by the improved awareness of motor vehicle drivers due to the presence of cyclists. However, as mentioned by Van Kempen et al. (2010), these studies only take the number of casualties that is registered by the police into account, while there is a large number of injured cyclists (especially due to crashes where cyclists crash with other cyclists, pedestrians or objects) that are not registered by the police. However, it should be mentioned that the estimations of Stipdonk & Reurings, 2010 and Van Kempen et al. (2010) are based on trips on average roads. In case specific infrastructural.
Development of a better understanding of the co-benefits associated with transport sector GHG reduction policies

EU Transport GHG: Routes to 2050?

Contract 070307/2010/579469/SER/C2

facilities for bicycles (cycling lanes, speed ramps, etc) are available, the traffic safety impacts of a modal shift from the car to cycling may be much better compared to cases without these facilities; in some specific cases the safety impacts of a modal shift to cycling may be even positive. No evidence on the safety impacts of a modal shift from the car to walking is available.

With regard to a modal shift from the car to public transport several effects should be taken into account. First the impact on the accident risk of the new public transport traveller himself. Since the accident risks of public transport are lower than the risks for passenger cars (SWOV, 2011), a shift from the car to public transport is beneficial for the traveller who performs this shift. Next, we consider the impact of the modal shift on the other traffic participants. Especially the aggressiveness (i.e. the accident risk they cause for other traffic participants) of local public transport modes (bus, tram) is larger than the aggressiveness of passenger cars. SWOV (2011) shows that the number of fatal and severe injury accidents per vehicle kilometre is 7 times higher for buses than for passenger cars. For trams, the number of fatal and severe injury accidents per vehicle kilometre is even 12 times larger than for cars. If only fatal accidents are taken into account these figures are 15 and 57 respectively. However, for a clear comparison of the aggressiveness of passenger cars and busses/trams the figures should be expressed per passenger kilometre. If we apply this correction, only busses with regard to fatal accidents score (slightly) worse than passenger cars: the number of fatal accidents per pkm is 1.5 times larger for busses than for passenger cars26. So, a shift from the car to public transport may in some cases result in a slightly reduction of traffic safety, but in general the impacts on traffic safety are considered to be positive.

5.2.3 Conclusion

In this section the impact of greenhouse gas reduction policies in transport on traffic safety have been studied. The GHG reduction policies may affect the number and severity of traffic accidents via various channels: changes in speed levels, traffic levels, vehicle characteristics, etc. Four specific policies were assessed in this chapter:

- Speed limits: a reduction in speed levels will probably result in lower accident risks and less severe accidents. A reduction in speed differences may contribute to these impacts.

- Road user charges: based on theoretical considerations it is expected that road charging schemes result in an improvement of traffic safety. This was confirmed by an ex-ante evaluation study on a road pricing scheme on all roads in the Netherlands. Evaluation studies on the congestion charges in London and Stockholm did not provide (statistically) significant results with regard to traffic safety.

- Vehicle standards; CO₂ emission standards leading to reductions in the average mass of vehicles will probably result in lower severity of accidents (due to a decrease in mass difference which is an important driver of accident severity). Introduction of hybrid/electric cars (on a large-scale) in the fleet may result in higher accident rates, since these vehicles may not be audibly detectable by pedestrians and cyclists. However, there are an adequate number of low cost solutions available to address this problem.

- Policies stimulating modal shift; a modal shift from the car to the bike will probably result in an increase in the total number of fatalities and injuries. On the other hand, the shift from the car to public transport will in most cases result in a slight improvement of traffic safety.

26 For this correction we assumed an occupancy rate of 1.6 for passenger cars and 16.4 for busses (based on TREMOVE). This implies that per vehicle kilometre a bus transports ca. 10 times more people than a passenger car. Hence, the number of fatal accidents per pkm is ca. 1.5 (15/10) times lower for busses than for cars.
5.3 Health benefits of increased levels of physical exercise

5.3.1 Introduction

GHG reduction policies can lead to an increased use of non-motorised transport modes, in particular cycling and walking. Besides various other co-benefits such as reduced pollutant and noise emissions, this can also result in personal health benefits from increased physical activity. Higher use of cycling and walking can increase the percentage of the population that meets the minimal physical activity level which is regarded to be required for a good health.

Cycling and walking can easily be integrated in daily life and can make that a healthy level of physical activity is sustained over time. Also increased use of public transportation can indirectly contribute to more physical activity, as it generally results in more cycling and walking to and from public transport stations.

According to the WHO, active transport modes are suitable for journeys of less than 5 kilometres (WHO 2004; Nordic Council et al. 2008). In Europe there is a large potential for cycling and walking. On average a European citizen cycles only 0.5 km per day, while the daily average distance by car is 28 km. More than 30% of trips made by car are less than 3 km and 50% of the trips are less than 5 km. Making these trips by non-motorised transport modes would result in 15-20 minutes cycling or 30-50 minutes brisk walking (Nordic Council, 2005).

In this chapter, the potential benefits of increased physical activity from a shift to cycling and walking are assessed. First, an overview is provided of the main health benefits from physical activity and the risks of inactivity (section 5.3.2). Then, in section 5.3.3, an overview is presented of studies that have attempted to quantify and monetize the health benefits from increased physical activity in the case of a shift to cycling and walking from the use of motorised transport. In section 5.3.4, an estimation is made of the potential health co-benefits at an EU scale. Finally, the overall conclusions are presented in section 5.3.5.

5.3.2 Physical activity and health effects

This section discusses the relationship between physical activity and health. First we give a brief overview of the recommended amount of physical activity in 5.3.2.1.1. Next, we provide an overview of the main health risks of inactivity.

5.3.2.1.1 Recommended physical activity

For a good health, adults are recommended to achieve a total of at least 30 minutes a day of moderate intensive physical activity on five or more days per week. Health benefits are the same when the 30 minutes are undertaken in one trip on day or split up into (minimum) ten minute periods. For children, the recommended physical activity is one hour of moderate activity (Chief Medical Officer/Department of Health, 2004; Nordic Council 2005).

Statistics show that in many cases those recommendations are not met. Overall levels of inactivity are high in developed as well as developing countries. According to the WHO, 60% to 80% of the world population does not meet the minimum level of recommended physical activity. For Europe the percentage of inactive adults is about 63%, ranging from 43% in Sweden to 88% in Portugal (Varo et al. 2003; WHO 2007; in De Hartog et al., 2010).
5.3.2.1.2 Health effects of physical inactivity

There is sufficient evidence for a relationship between physical activity and mortality, cardiovascular disease (hypertension), diabetes, obesity, cancer (colon and breast), osteoporosis and depression (De Hartog et al., 2010). Below we give a brief overview of the main health risks of inactivity.

**Mortality**

There are various estimates for the number of people worldwide that die due to physical inactivity. The WHO estimated this to be 1.9 million in 2002 (Medibank, 2008). The relationship is an inverse dose-response relationship: as the level of the physical activity increases, the risk of all-cause mortality decreases. Cycling to work decreases the risk of premature death by around 40% (Chief Medical Officer/Department of Health 2004).

**Cardiovascular diseases**

For cardiovascular diseases the percentage of occurrences is around 22% (The PEP, 2009). According to the National Heart Forum in the UK, 37% of chronic heart diseases (CHD) can be attributed to physical inactivity and 9% of all CHD is avoidable in case people become moderately active (Chief Medical Officer/Department of Health, 2004). People only have reduced risk of cardiovascular diseases during the period that they meet the minimum level of physical activity. In cases where lifestyle is changed in a physical inactive lifestyle, the benefit disappears (SQW, 2007). Physical activity can also decrease blood pressure and the associated health risks.

**Type 2 Diabetes**

Physical inactivity can increase the risk of developing Type 2 Diabetes by 33-50%. This type of diabetes which is also known as adult-onset diabetes can have long-term complications, such as increased risk of heart attacks, strokes, amputation, and kidney failure.

Being physically active can contribute to prevention of this disease and in the case of a person who has developed diabetes, physical activity can lead to a reversal or delay of complications (Cavill and Davis, 2007).
Cancer
Physical activity can reduce the risks of different forms of cancer. The strongest evidence exists for colon cancer, where physical activity results in an average risk reduction of 40-50%. Another form of cancer related to the level of physical activity is breast cancer. For other forms of cancer there is not sufficient evidence at the moment (Cycling England, 2007). The WHO estimates that 10% to 16% of all occurrences of breast, colon and rectal cancers and diabetes mellitus are caused by physical inactivity.

Overweight and obesity
Many parts of the world deal with an epidemic of obesity. It is not only adults who are dealing with high Body Mass Indexes (BMI), but the problem of obesity is also increasing among young adults and children. Undertaking moderate intensity lifestyle activities for an additional half hour per day with dietary intervention is similar to three aerobic classes a week and can contribute to reduced weight and obesity (Cycling England, 2007).

Mental health and well-being
Physical activity is associated with improved mental health, like self esteem, body image and self-perception. The effects are stronger for people having a low self-esteem like mental health patients and patients suffering a mild depression. Being active also reduces symptoms of anxiety or emotional distress and can have a positive effect on sleep patterns. (Cycling England, 2007).

5.3.3 Quantification and monetization of the health effects of physical (in)activity

There are various studies available on the quantification of health effects of an increased use of active transport modes. Total benefits can be expressed in different ways, like higher life expectancy, impacts on the average Body Mass Index (BMI) or the disability-adjusted life year (DALY). Some examples are given in 5.3.3.1.1. Various economic studies value the benefits from extra cycling and walking per year or per kilometre. An overview of this is presented in section 5.3.3.1.2.

5.3.3.1.1 Quantification of the health effects of physical (in)activity

Some studies have investigated to what extent the health benefits due to a modal shift from car to bike outweigh the health risks of this same modal shift. While increased physical activity can result in benefits, a cyclist inhales more pollutants due to an increased breathing rate and the risk to get involved in an accident may be higher, as well as the severity of accidents. De Hartog et al. (2010) concluded that the overall health benefits are substantially larger than the estimated health risks compared to driving a car. The increased physical activity of cycling can result in 3-14 months higher life expectancy. This exceeds the loss of life expectancy related to inhaled air pollution doses, which is estimated at 0.8 – 40 days and the loss due to higher accident risks, estimated at 5 – 9 days (De Hartog et al, 2010).

MacDonald et al. (2010) performed a study on the effect of using light rail transit (LRT) system on BMI, obesity, and weekly recommended physical activity levels. A significant correlation was found between light rail transit use and long term effects on BMI. By walking to the light rail transit, travellers reduced their BMI by an average of 1.2 kg/m² compared to non-users, over a period of 12-18 months. Light rail transit users were 81% less likely to become obese over time, but the association between light rail transit use and meeting weekly recommended physical activity levels of walking was not significant (Mac Donald et al., 2010).

5.3.3.1.2 Monetization of the health effects of physical (in)activity

Physical inactivity is a problem, because it threatens common health. The consequences of physical inactivity as summarized in section 5.3.2 can also be expressed in financial terms. Comparing physical inactivity with alcoholism, surplus hospitalization expenditure is equal.
Compared to smoking, the cost of physical inactivity are half as high, but just looking at the mortality rates, the risks are equal (Nordic Council 2005). Physical activity can prevent health care costs, absence at work and can increase productivity.

Various studies have monetized the health effects of increased physical activity due to increased use of non-motorised transport modes. Some of these studies are hard to compare, because results are expressed in very different units e.g. total benefits of a specific infrastructure project or refer very specific case studies. We found two studies that can be used to derive estimates on a national level: SQW (2007) and NZ Transport Agency (2008). Both studies used a broad literature analysis, including many of the other (case) studies on monetization.

The costs of inactivity and obesity (related to the diseases mentioned above) are estimated for England by SQW (2007), based on different sources, as presented in Table 5.4. The annual social costs sum up to roughly 10 billion Euro. A very rough linear extrapolation of these cost to the whole EU would result in cost of inactivity of about 100 billion Euro.

Table 5.4: The costs of inactivity and obesity for England (source: SQW, 2007)

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Value per year</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs of physical inactivity (including treatment of disease and indirect costs of sickness absence)</td>
<td>€9.6 billion</td>
<td>CMO (2004)(uses the high estimate)</td>
</tr>
<tr>
<td>Cost of physical inactivity</td>
<td>€2.2 - €9.6 billion</td>
<td>DCMS/Strategy Unit (2002)</td>
</tr>
<tr>
<td>- direct costs to NHS</td>
<td>- €0.4 - €2 billion</td>
<td></td>
</tr>
<tr>
<td>- earnings lost due to sickness</td>
<td>- €0.9 – €6.3 billion</td>
<td></td>
</tr>
<tr>
<td>- earnings lost due to premature mortality</td>
<td>- €0.9 – €1.2 billion</td>
<td></td>
</tr>
<tr>
<td>Cost of obesity to NHS (direct costs of treating obesity)</td>
<td>€1.2 - €1.3 billion (2002 values)</td>
<td>HoC Scrutiny Unit (2004)</td>
</tr>
<tr>
<td>Cost of obesity to the wider economy (indirect costs relating to loss of output due to illness or death resulting from obesity)</td>
<td>€2.7 - €3.1 billion (2002 values)</td>
<td>HoC Scrutiny Unit (2004)</td>
</tr>
</tbody>
</table>

SQW (2007) does not present health benefit values per kilometre, but it includes data per year of cycling for adult cyclists. It is assumed cyclists travel an average of 3.9 km per trip and make 160 trips a year. This implies 3 trips a week with a total of 624 km/year. SQW has differentiated for the age of cyclists. As can be seen in Table 5.5, the benefits for a cyclist of 65 years or older are substantially higher: €208 in comparison to €103 for 16-44 year old age group.
Table 5.5: Summary of health benefit values per year for adult cyclists (source: SQW, 2007)

<table>
<thead>
<tr>
<th>Health benefit</th>
<th>Values per year of cycling</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values of loss of life</td>
<td>€13 for 16-44 year olds</td>
<td>SQW estimates based on NHF data</td>
</tr>
<tr>
<td></td>
<td>€11 7 for 45-64 year olds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>€287 for 65 year olds and over</td>
<td></td>
</tr>
<tr>
<td></td>
<td>€70 average</td>
<td></td>
</tr>
<tr>
<td></td>
<td>€34 for all cyclists</td>
<td></td>
</tr>
<tr>
<td>NHS savings</td>
<td>€56 all cyclists</td>
<td></td>
</tr>
<tr>
<td>Productivity gains</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total health benefits</td>
<td>€103 for 16-44 year olds</td>
<td>Assumes a full year of cycling by adult</td>
</tr>
<tr>
<td></td>
<td>€208 for 45-64 year olds</td>
<td>Note that older people will tend to have higher values</td>
</tr>
<tr>
<td></td>
<td>€189 average</td>
<td></td>
</tr>
<tr>
<td>Child health and obesity</td>
<td>Not quantified</td>
<td>Requires a different approach based on cycling as an investment in reducing future health costs</td>
</tr>
</tbody>
</table>

Another study that monetized the benefits of increased physical activity of non-motorized transport modes was carried out by NZ Transport Agency (2008) in New Zealand. It states that traditional economic evaluation methods tend to undervalue public health benefits provided by active transport modes. Benefits that are not included in the traditional methods are for example the health benefits for already existing pedestrians, the effects for other active mode users (skates and scooters) and increased productivity.

In NZ Transport Agency (2008), a value of statistical life (VoSL) was used, expressing the willingness-to-pay (WTP) for increased life expectancy and reduced disability. The values given in Table 5.6 apply to all new walkers and cyclists. According to NZ Transport Agency (2008) the benefits of those who already walk and cycle are about half as high (NZ Transport Agency 2008). In this way the health effects of current users are taken into account, because investments in new cycling and walking infrastructure may reduce the likelihood those users to switch to another transport mode later. The health benefits would not be lost in this case.

Table 5.6: Per-kilometre benefits in Euro (source: NZ Transport Agency . 2008)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual benefit</th>
<th>Per km walking</th>
<th>Per km cycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>€1,738</td>
<td>€1.97</td>
<td>€0.99</td>
</tr>
<tr>
<td>Medium</td>
<td>€2,101</td>
<td>€2.38</td>
<td>€1.19</td>
</tr>
<tr>
<td>High</td>
<td>€2,465</td>
<td>€2.80</td>
<td>€1.40</td>
</tr>
</tbody>
</table>

In Table 5.7 the results of both studies are compared. The annual benefit found by SQW (2007) is less than 10% of the average annual benefit found by NZ Transport Agency (2008). The average annual benefit of €189 from SQW (2007) is expressed in a per kilometre price. Dividing the average of €189 by the total of 624 km/year results in €0.30 per kilometre, which is four times smaller than the €1.19 found by NZ Transport Agency. Note that SQW is focused on cycling, while NZ Transport Agency has considered both cycling and walking. The differences can also be explained by the fact that both studies were carried out for different countries, using different national data. NZ Transport Agency has also performed a meta-analysis of different literature studies.
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Table 5.7: Annual benefit and benefit per km cycling (NZ Transport Agency, 2008; SQW, 2007)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual benefit</th>
<th>Per km cycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>€1,738</td>
<td>€189</td>
</tr>
<tr>
<td>Medium</td>
<td>€2,101</td>
<td>€1.19</td>
</tr>
<tr>
<td>High</td>
<td>€2,465</td>
<td>average</td>
</tr>
</tbody>
</table>

5.3.4 Estimation of effects of GHG policies on annual benefits from increased physical activity

It is hard to predict the change in activity due to GHG policies. This can vary strongly by policy measure and there is a mix of other factors which influence the individual choice for a modality. GHG policies will be implemented parallel to health policies. It can therefore be difficult to identify the health effects as co-benefits of GHG policies.

However, based on above findings, an indication can be retrieved of the size of the co-benefits of GHG reduction policies in relation to an increase in physical activity.

The following figures are used for deriving an estimate of the co-benefits for the whole of the EU:
- Total inhabitants of EU-27: 495 million inhabitants
- Current inactivity level in EU-27: 62.2% = 308 million inhabitants
- Benefits of physical activity per person per km: €0.30-€1.20
- Number of cycling kilometres per year for an active person: 1,000 km

In Table 5.8 the total annual benefits from physical activity are presented for a few illustrative scenarios. Because there are no predictions to what extent GHG policies will lead to an increase in bicycle use and walking, calculations are made for two scenarios:
1. 10% of the inactive inhabitants become active
2. 33% of the inactive inhabitants become active.

For both scenarios, the benefits have been valued with the higher and lower valuation.

Table 5.8: Estimations of total annual benefits from physical activity

<table>
<thead>
<tr>
<th>Inactive inhabitants becoming active (x million)</th>
<th>Benefits per person per year</th>
<th>Total annual benefits (x billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.8 (10%)</td>
<td>€300 (low)</td>
<td>€9</td>
</tr>
<tr>
<td>30.8 (10%)</td>
<td>€1,200 (high)</td>
<td>€37</td>
</tr>
<tr>
<td>101.6 (33%)</td>
<td>€300 (low)</td>
<td>€31</td>
</tr>
<tr>
<td>101.5 (33%)</td>
<td>€1,200 (high)</td>
<td>€122</td>
</tr>
</tbody>
</table>

These calculations indicate that the potential co-benefits of increased physical activity can be very significant, ranging from 9 up to more than 100 billion Euro per year. Even in the case where only 10% of the inactive Europeans start to cycle or walk regularly, the benefits are still in the range of 9 to 37 billion Euro a year, depending on the type of valuation used.
5.3.5 Conclusion

Physical inactivity can lead to different health effects. Chronic heart disease, type 2 diabetes, cancer and obesity are all diseases which are to a certain extent linked to physical inactivity. About 60% to 80% of the world population does not meet the minimum level of recommended physical activity of at least 30 minutes a day of moderate intensity physical activity on five or more days per week. Physical inactivity can lead to, for example, higher health care costs and lower productivity.

GHG policies can contribute to reducing the level of physical inactivity. In situations where more active transport modes are stimulated, more people will cycle and walk. The health benefits gained by reducing physical inactivity can be quantified and monetized. The per km health benefits from increased physical activity from cycling vary from €0.30 to around €1.20. Based on these numbers, indicative estimates were made for the total potential benefits in the EU. They range from 9 to 37 billion in case that 10% of the inactive people would become active because of increased use of cycling and walking. In case that a third of the inactive population would become active, the benefits would even be in the range of 31 to 122 billion Euro per year. The ranges in these estimates reflect uncertainties in quantification of the benefits.

Overall, it can be concluded that the health effects of increased physical activity represent significant financial benefits and therefore should also be taken into account when assessing the cost-effectiveness of transport and climate policies.

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6 Indications of the Relative Values of the Different Co-benefits and Conclusions

Objectives:
The purpose of this sub-task was to:

- Develop indications of the relative values of the different co-benefits, including:
- Development of a semi-quantitative method for comparing the relative values of co-benefits;
- Take account evidence on the scale of importance of each co-benefits to the wider community of the EU.

Summary of Main Findings
- Work pending completion of other subtasks. To be completed after November Focus Group Meeting