Published Project Report
PPR358

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Emission factors 2009: Report 5 – a review of the effects of fuel properties on road vehicle emissions

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TRL Limited

PUBLISHED PROJECT REPORT PPR358

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Version: 3

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Executive Summary

TRL Limited was commissioned by the Department for Transport to review the methodology used in the National Atmospheric Emissions Inventory (NAEI) for estimating emissions from road vehicles. Various aspects of the methodology were addressed, and new exhaust emission factors for road vehicles were derived (this is described in a separate Report).

This Report describes the effects of fuel properties on exhaust emissions. It examines the need for correction factors to model the effects of any differences between the fuels used for emission factor derivation and the fuels which are representative of the UK market, now and in the future.

The main topics covered in the Report are:

(i) The effects of fuel sulphur content on exhaust emissions
(ii) The effects of other fuel parameters on exhaust emissions.
(iii) The effects on emissions of biofuels and other alternatives to petroleum petrol and diesel.
(iv) The modelling of fuel effects.
(v) The implications of fuel effects on the UK emission factors.

The sulphur content of fuel in the European Union has reduced considerably in recent years. From 1999 all UK diesel had a sulphur level of less than 50 ppm. From 2001 all UK petrol also had a sulphur level of less than 50 ppm. Since 1 January 2009 all UK fuel has contained less than 10 ppm sulphur. Two aspects of fuel sulphur content are reviewed: (i) the effects of switching form ‘ultra-low sulphur’ fuels (50 ppm sulphur) to sulphur-free fuels (10 ppm sulphur), and (ii) the potential ‘catalyst recovery’ associated with a reduction in fuel sulphur content. Within a given emission class the effects of fuel sulphur content on NO_x and PM emissions are generally either not significant or rather small. Reductions in fuel sulphur content from 50 ppm to 10 ppm seem unlikely to bring substantial emissions benefits for current Euro 3/III and 4/IV vehicle technologies. The main exception may be PM emissions. Emissions from modern petrol Euro 3 and Euro 4 cars do not appear to show a change in sensitivity to fuel sulphur level with age. It is possible that older petrol vehicles could show some degree of catalyst recovery (*i.e.* lower emission levels) when used on sulphur-free fuel. However, such effects are rather difficult to quantify as there seems to be little interest in testing old vehicles on new fuels.

Lowering fuel aromatic content will generally result in reduced PAH emissions from older technology engines. Diesel vehicles with after-treatment devices are less sensitive to the fuel aromatic content. An increase in cetane number generally results in a decrease in emissions of CO, HC and NO_x. Again, for diesel vehicles equipped with oxidation catalysts or PM filters, emissions will generally tend to be less sensitive to cetane number. The effects on PM appear to be rather variable. Changes in other fuel properties, such as volatility and olefin content, can also result in small, sometimes significant, changes in emissions.

The effects on exhaust emissions of two main types of biofuel are briefly reviewed: biodiesel blends and ethanol blends. These are the main biofuels available in the UK. There is a general agreement in the literature that biodiesel (and its blends) reduces exhaust emissions of CO, HC and PM, whereas NO_x emissions from biodiesel appear to increase. However, the blending of petroleum diesel with biodiesel in a proportion of less than 10% is expected to have no effect on emissions, and the biofuel content of diesel is not predicted to exceed 5% by volume, although under a revision of the fuel specification EN590 in September 2009 suppliers may supply fuel with a bio-content of up to 7%. Studies have generally shown that ethanol/petrol blends reduce CO, HC and PM emissions, but also that vehicles with newer technologies show smaller reductions compared to vehicles with older technologies. The effect of blends on NO_x emissions are mixed, and exhaust CO_2 emissions appear not to be greatly affected.

In order to the derive fuel composition scaling factors, an adapted version of the method presented in COPERT III/4 is proposed. Fuel composition scaling factors are given for all light-duty and heavy-duty vehicles. The resulting scaling factors should be used in conjunction with the emission factors which have been derived in the project. From the evidence it appears that emission scaling factors for biodiesel and ethanol are not required in the UK.

1 Introduction

Emissions of air pollutants in the United Kingdom are reported in the National Atmospheric Emissions Inventory (NAEI)[1]. Estimates of emissions are made for the full range of sectors, including agriculture, domestic activity, industry and transport. The results are submitted by the UK under various international Conventions and Protocols, and are used to assess the need for, and effectiveness of, policy measures to limit or reduce UK emissions. Projections from the road transport sub-model in the NAEI are used to assess the potential benefits of policies, technological developments and future emission standards for new vehicles. It is therefore essential that the model is as robust as possible and is based on sound data.

TRL Limited has been commissioned by the Department for Transport (DfT) to review the methodology currently used in the NAEI to estimate emissions from road vehicles. The overall purpose of the project is to propose a complete methodology for modelling UK road transport emissions. The project includes an extensive and detailed review of the current methodology, identifies where approaches could improve the quality of the emission estimates, and shows where existing methodologies give good quality estimates and should be retained.

The specific objectives of the project take the form of a list of Tasks. These Tasks, which are self-explanatory, are:

- Task 1: Review of the methods used to measure hot exhaust emission factors, including test cycles and data collection methods (Boulter *et al.*, 2009a).
- Task 2: Review of the use of average vehicle speed to characterise hot exhaust emissions (Barlow and Boulter, 2009).
- Task 3: Development of new emission factors for regulated and non-regulated pollutants (Boulter *et al.*, 2009b).
- Task 4: Review of cold-start emissions modelling (Boulter and Latham, 2009).
- Task 5: Reviewing the effects of fuel quality on vehicle emissions (this Report).
- Task 6: Review of deterioration factors and other modelling assumptions (Boulter, 2009).
- Task 7: Review of evaporative emissions modelling (Latham and Boulter, 2009).
- Task 8: Demonstration of new modelling methodologies (Boulter *et al.*, 2009c).
- Task 9: Final report (Boulter *et al.*, 2009c).

Task 1 also included the compilation of a Reference Book of driving cycles (Barlow *et al.*, 2009).

This Report presents the findings of Task 5, the overall aim of which was to review the effects of fuel quality – or rather fuel *properties* – on exhaust emissions from road vehicles. The effects of fuel properties on evaporative emissions are covered by Latham and Boulter (2007). The Report reviews the need for correction factors to model the effects of differences between the properties of the fuels used for emissions factor testing and the fuels which are representative of the UK market, and to provide relevant recommendations for the NAEI. This requires:

(ii) An understanding of the changes in UK fuel composition which have happened in the past and those which are likely to happen in the future.

(iii) An understanding of the effects of changes in fuel properties on emissions. A number of research studies have been carried out to investigate the influence of fuel properties on emissions. The most comprehensive programmes include the European Programme on Emissions, Fuels and Engine Technologies (EPEFE) (ACEA and EUROPIA, 1996) and the American Auto/Oil Air Quality Improvement Research Program (Burns, 1991).

(iv) An understanding of how fuel effects are taken into account in the NAEI.

Historically, fuel properties have been dependant upon crude oil economics and refinery technology. More recently the main drivers have been exhaust emission standards and the technologies required to meet them. This has resulted in some significant changes in fuel composition, particularly with respect to sulphur content.

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[1] http://www.naei.org.uk/

The sulphur content of fuel in the European Union has reduced considerably in recent years. For diesel fuel a maximum sulphur limit of 50 parts per million (ppm) – known as 'ultra-low sulphur' (ULS) - was introduced on 1 January 2005 by Directive 2003/17/EC. The UK introduced this earlier. However, although small improvements in emissions have been achieved by reducing sulphur to these low levels, several emission-control technologies are intolerant to sulphur and require that levels are reduced even further. Directive 2003/17/EC therefore also required 'sulphur-free' petrol and diesel fuels - with a limit of 10 ppm - to be available on an 'appropriately balanced geographical basis' by 1 January 2005. All UK road diesel has had a sulphur level of less than 50 ppm since 1999 (since 2001 for petrol), and since 1 January 2009 all road fuel has had less than 10 ppm sulphur.

Such changes in fuel composition should be taken into account in the development of exhaust emission factors for road vehicles in the UK. As some of the emission factors currently in use were determined from tests using fuels with a relatively high sulphur content, the NAEI currently applies correction factors – more specifically, to diesel vehicle PM emissions. More recent emission tests will have been conducted using either UK-specification ULS fuels (for diesel this involves a lower density and T95[2] level than required by European Union law), or using sulphur-free fuels.

It is worth noting that the investigation of fuel effects on exhaust emissions, and the subsequent application of the resulting knowledge in the development of emission factors, is rather more complex than the above discussion would suggest. It requires a strict test protocol to ensure that any emission variation observed is actually due to the different properties of test fuels, and not to other factors. During the measurements the fuel change and vehicle conditioning procedure is critical, and the tank and the fuel system must be thoroughly flushed with the new fuel in order to reduce the possibility of carry-over effects. Importantly, the test vehicle needs to be conditioned to permit the engine management system to adapt to the new fuel (Martini *et al*., 2007). In spite of such rigorous requirements, the results of studies are often inconclusive or contradictory, making it difficult to quantify emission trends. The observed scatter of data may be attributed a number of factors, including variability in the properties of the fuels and/or blending stock, the use of different types of engine and the use of different test cycles. In order to study the effect of a specific fuel property on emissions, care must be taken to decouple the change in a particular fuel property from changes in other properties of the test fuel. Some studies have not decoupled the fuel properties adequately. If a number of fuel properties are changed simultaneously it is not possible to ascribe any emission changes to a change in one property. Furthermore, reported relative emission effects may be distorted due to the use of different baseline fuels. Despite the wealth of experimental data, the influence of some fuel properties on emission is still not clear (Majewski and Jääskeläinen, 2005).

Chapter 2 of the Report describes the specifications of fuels which are currently used in the UK. In Chapter 3 the effects of changes in fuel sulphur content on exhaust emissions are reviewed, and Chapter 4 covers the effects of changes in other fuel parameters. Chapter 5 considers the effects of biofuels and other alternatives to petroleum petrol and diesel. The modelling of fuel effects is described in Chapter 6. The implications of fuel-related effects on the UK emission factors are considered in Chapter 7. Chapter 8 of the Report gives the summary, conclusions and recommendations of the work.

In the measurement and modelling of vehicle emissions various abbreviations and terms are used to describe the concepts and activities involved. Appendix A provides a list of abbreviations and a glossary which explains how specific terms are used in the context of this series of Reports.

It should also be noted that, in accordance with the legislation, a slightly different notation is used in the Report to refer to the emission standards for light-duty vehicles (LDVs)[3], heavy-duty vehicles (HDVs)[4] and two-wheel vehicles. For LDVs and two-wheel vehicles, Arabic numerals are used (*e.g.* Euro 1, Euro 2…*etc.*), whereas for HDVs Roman numerals are used (*e.g.* Euro I, Euro II…*etc.*).

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[2] T95 is the temperature at which 95% of a particular diesel fuel distills in a standardised distillation test (ASTM D 86). Reducing T95 decreases NO_x emissions slightly, but increases hydrocarbon and CO emissions. PM_{10} emissions are unaffected.

[3] Light-duty vehicles are vehicles weighing less than or equal to 3.5 tonnes, including cars and light goods vehicles (LGVs). LGVs are sometimes also referred to as 'light commercial vehicles', 'light trucks' or 'vans' in the literature. The term LGV is used in this Report.

[4] Heavy-duty vehicles are all vehicles heavier than 3.5 tonnes, including heavy goods vehicles (HGVs), buses and coaches.

2 Automotive fuels in the UK

The main types of fuel sold at UK retail outlets are the following[5]:

- Unleaded petrol (95 octane).
- Super unleaded petrol (97/98/99 octane).
- Diesel.
- Super diesel.
- Liquefied petroleum gas (LPG).

According to UKPIA (2006), sales of petrol have been falling since reaching a peak of 33 billion litres in 1990, and currently represent approximately 52% of road transport demand by volume. Sales of diesel have been steadily increasing for the last twenty years, and currently represent around 48% of road transport demand by volume. Petrol and diesel therefore account for virtually all of the fuel sold in the UK. Sales of LPG rose rapidly between 2000 and 2005 as a result of a favourable duty incentive. However, sales of new LPG/petrol cars declined significantly in 2005.

The European Union and UK regulations governing the composition of automotive fuels are summarised in the following Sections.

2.1 European Union regulations on fuel composition

The composition of automotive fuels in the European Union (EU) is specified by standards developed by the European Standards Organisation (CEN). The first set of standards for automotive fuels, ratified by CEN on 16 March 1993, became mandatory in all Member States in September 1993: EN228 for petrol, EN590 for diesel, and EN589 for LPG. The standards are periodically updated to reflect changes in specifications, such as the mandatory reductions in sulphur content. To provide options for different climates, the EN590 standard specifies six ‘Temperature Climate Grades’ of diesel fuel (Grades A to F). In addition, there are five ‘Arctic Classes’ of diesel fuel (Classes 0 to 4) which are characterised by different properties. Each country must state its requirements for summer-grade and winter-grade fuel, and may also include intermediate or regional grades as justified by climatic conditions.

Mandatory environmental fuel specifications have been introduced in EU Directives. The following are the most important recent steps in the evolution of fuel specification:

- Directive 98/70/EC of 13 October 1998 relating to the quality of petrol and diesel fuels, and amending Council Directive 93/12/EEC.
- Directive 2000/71/EC of 7 November 2000 to adapt the measurement methods laid down in Annexes I, II, III and IV of Directive 98/70/EC to technical progress, as foreseen in Article 10 of that Directive.
- Directive 2003/17/EC of 3 March 2003 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels.

In addition, Directive 2003/30/EC aims to promote the use of biofuels, or other renewable fuels, as substitutes for petrol or diesel in the transport sector.

2.1.1 Directive 98/70/EC

This Directive set the environmental specifications which were applicable to fuels for vehicles equipped with positive ignition (petrol) and compression ignition (diesel) engines. Leaded petrol was banned from the market from the year 2000 onwards. The Directive also provided for progressive improvements in the ‘environmental quality’ of unleaded petrol and diesel fuel. The environmental requirements covered the following:

- *Unleaded petrol*: octane level, vapour pressure and distillation by evaporation, as well as content of aromatics, benzene, olefins, oxygen, oxygenates, sulphur and lead.

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[5] http://www.ukpia.com/industry_information/marketing_and_retailing.aspx

- *Diesel*: cetane number[6], density, distillation, PAHs and sulphur content.

According to the Directive, by 1 January 2000 the maximum limit value for sulphur in diesel fuels was 350 ppm and the minimum cetane number was 51. By 1 January 2005, the maximum limit for sulphur in diesel was 50 ppm and ‘sulphur-free’ (10 ppm sulphur) diesel had to be available for road vehicles.

Member States could, in certain specific cases, allow petrol or diesel fuels which failed to comply with the Directive to remain on the market, and the marketing of small quantities of leaded petrol was still authorised after 1 January 2000 for use in certain vehicles. Member States could also impose more stringent standards on fuels marketed on their territory in order to protect the environment or public health in a specific ecologically sensitive area, provided the measures were restricted to those areas. Member States were required to monitor compliance with the environmental requirements for fuels using the analytical methods defined by the Directive.

2.1.2 Directive 2000/71/EC (amendment to Directive 98/70/EC)

Directive 98/70/EC gave the environmental specifications for unleaded petrol and diesel fuels, and also the methods to be used by both industry and enforcement agencies when testing for compliance with those specifications. The test methods incorporated into Directive 98/70/EC pre-empted the methods that were under development by CEN. These were subsequently published in EN228 for petrol and EN590 for diesel after the adoption of 98/70/EC. The final CEN Standards, however, included revisions to the numbering of the documents that detailed each test method, and included detailed changes within the documents themselves. This rendered them different to the test methods itemised in the Directive. The purpose of Directive 2000/71/EC 7 November 2000 was therefore to realign the test methods specified in Annexes I, II, III and IV of Directive 98/70/EC with the published CEN Standards.

2.1.3 Directive 2003/17/EC (amendment to Directive 98/70/EC)

Directive 2003/17/EC required Member States to ensure that unleaded petrol and diesel fuels with a maximum sulphur content of 10 ppm were marketed within their territories by no later than 1 January 2005. By no later than 1 January 2009 the Member States had to ensure that all unleaded petrol and diesel fuels complied with the environmental specifications for fuel for highway and non-road vehicles set out in the Directive, and were available on a balanced geographical basis.

These fuels should enable the optimisation of new petrol engine technologies (such as lean-burn, direct-injection engines) for maximum fuel and CO_2 emissions savings. In addition, they ought to improve the efficiency of certain emission-control systems, and so reduce emissions of pollutants which are harmful to health.

Member States must introduce a fuel quality monitoring system and, by no later than 30 June of each year, present a fuel quality report. In turn, the European Commission must publish an annual report on fuel quality in the Member States and on the geographical coverage of fuels with a maximum sulphur content of 10 ppm. Member States must introduce penalties for infringements of the Directive.

2.1.4 Directive 2003/30/EC (‘Biofuels Directive’)

Directive 2003/30/EC - the ‘Biofuels Directive’ - was agreed by the European Council and Parliament on 8 May 2003. The main objectives of the Directive are to reduce life-cycle emissions of carbon dioxide from transport across Europe, and to reduce the EU’s future reliance on external energy sources (in this case, oil). The Directive aims to promote the use of biofuels, or other renewable fuels, as substitutes for petrol or diesel in the transport sector. It requires Member States to set indicative targets for biofuels sales for 2005 and 2010, and to introduce a specific labelling requirement at sales points for biofuel blends in excess of 5%.

The term ‘biofuel’ is a generic one used to describe liquid or gas fuels which are either not derived from fossils fuels, or contain a proportion of non-fossil fuel. Biofuels fall into two main categories: conventional biofuels produced from plants (crops such as sugar cane/beet and wheat for ethanol, and rape seed oil or re-

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[6] Cetane number (CN) is a measure of the combustion quality of diesel fuel.

processed vegetable oils for biodiesel), and advanced biofuels from gasified biomass. At present, most biofuels fall into the conventional category. Although biofuels can be used as road fuels on their own, mostly they are blended with conventional petrol or diesel fuel. Directive 2003/17/EC currently limits the concentration of biofuel content of conventional petrol and diesel to 5% by volume[7].

The Directive requires Member States to take account of the reference values prescribed in Article 3(1) in setting their national indicative targets. These reference values are:

- 2% (calculated on the basis of energy content) of all petrol and diesel for transport purposes placed on their markets by 31 December 2005.
- 5.75% (again based on energy content) of all petrol and diesel for transport purposes placed on their markets by 31 December 2010.

In early 2007 European energy ministers set a target of 10% for 2020.

Member States must also report to the Commission each year on the measures taken to promote the use of biofuels and on levels of biofuel sales. Although the Directive is clear that Member States are free to set their own indicative targets, it specifies that the annual reports to the Commission should justify any differentiation between the proposed national targets and the Directive's reference values.

It should be noted that the reference values are calculated on the basis of energy content. Translating these reference values into equivalent values on the basis of sales by volume or mass is not straightforward. Biodiesel and bioethanol both contain less energy content per unit of volume than fossil fuels, but the difference is more pronounced for bioethanol. Translating the 2% and 5.75% reference values into percentages of sales by volume will therefore depend, amongst other things, on the anticipated split between biodiesel and bioethanol sales.

Two sets of standards establish the specifications for biodiesel fuels in the European Union:

- EN 14214 includes specifications for fatty acid methyl ester (FAME) fuel for diesel engines. B100 that meets this standard could be used unblended in a diesel engine (if the engine has been adapted to operate on B100) or blended with petroleum diesel fuel.
- EN 590, the European diesel fuel specification, is also applicable to biodiesel blends up to 5% of FAME.

2.2 UK regulations on fuel composition

2.2.1 Motor Fuels (Composition and Content) Regulations 1999

The Motor Fuel (Composition and Content) Regulations 1999 transposed EU Directive 98/70/EC into UK law. The Regulations specified minimum environmental and operational requirements for petrol, diesel and LPG.

Fuels had to meet the requirements of the following British Standards:

- 95 octane unleaded petrol - BS EN 228:2004
- 97 octane unleaded petrol - BS 7800:2000
- Diesel - BS EN 590:2004
- LPG – BS EN 589:2004

One of the fuel quality parameters which was regulated was the sulphur content. The UK government decided to introduce low-sulphur fuels in the UK earlier than specified in Directive 98/70/EC. UK ultra-low sulphur fuels were required by the Regulations to meet the following additional requirements:

- Petrol - for those grades listed above, a maximum sulphur content of 50 ppm (as opposed to 150 ppm allowed in Directive 98/70/EC), and a maximum aromatics content of 35% volume (as opposed to 42% in Directive 98/70/EC).
- Diesel – a maximum sulphur content of 50 ppm (as opposed to 350 ppm allowed in Directive 98/70/EC), and a maximum density of 835 kg m^{-3} (as opposed to 845 kg m^{-3} in the Directive). This

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[7] http://www.ukpia.com/industry_issues/fuels/alternative_fuels.aspx?referrertabid=2107&linktext=Alternative+Fuels

density parameter will align with the 2003/17 Directive requirements when 10 ppm fuels become available.

2.2.2 The Motor Fuel (Composition and Content) (Amendment) Regulations 2001

The primary objective of these Regulations was to implement into UK law EU Directive 2000/71/EC concerning the quality of petrol and diesel fuels, in order to introduce updated test procedures for certain fuel parameters. The opportunity was also taken to simplify the 1999 Regulations in relation to Leaded Petrol Permits. Directive 98/70/EC introduced a general ban on the sale of leaded petrol, but with a dispensation that allowed Member States to continue marketing a small quantity (0.5% of total petrol sales) to take account of the ongoing needs of old and historic vehicles. To make certain that sales could not exceed this limitation, the 1999 Regulations introduced a Leaded Petrol Permit Scheme that fixed the total amount of leaded petrol that could be sold annually by every distributor. The Scheme also applied a limit on the amount of leaded petrol that could be distributed to filling stations each month to ensure that it was available throughout the whole year. After the scheme was set up, actual sales of leaded petrol fell to very low levels, thus making the need to control monthly supplies, and the monthly reporting system that this entailed, unnecessary. The Regulations therefore aimed to dispense with this requirement.

2.2.3 The Motor Fuel (Composition and Content) (Amendment) Regulations 2006

These Regulations further amended the 1999 Regulations in order to implement Directive 2003/17/EC. From 1 January 2005 all petrol and diesel fuels were required to contain no more than 50 ppm sulphur, and from 1 January 2009 this reduced to 10 ppm. A further requirement of Directive 2003/17/EC is that sulphur-free fuel be available on an ‘appropriately balanced geographical basis’ in advance of 2009.

The Regulations also provide for a maximum vapour pressure for petrol during the summer period that accords with the specification contained in the Directive. In order to satisfy the summer petrol requirement the vapour pressure of petrol must not exceed 70 kPa.

2.2.4 The Renewable Transport Fuel Obligation (RTFO)

In response to EU Directive 2003/30EC, since April 2008 the RTFO programme has placed an obligation on fuel suppliers to ensure that a certain percentage of their aggregate sales is made up of biofuels. The original RTFO targets envisaged a biofuel content of 3.75% in 2009/10 rising to 5% in 2010/11. However, in January 2009 the RTFO limits were revised. The yearly obligations for fuel suppliers under the RTFO will now be as follows:

- 3.25% for 2009/10
- 3.5% for 2010/11
- 4.0% for 2011/12
- 4.5% for 2012/13
- 5.0% for 2013/14

The new levels are in line with recent recommendations in the Gallagher Review[8] of Biofuels, which advised a slowing down in the rate of increase of biofuel content in road fuels to reach 5% in 2013/14.

The UK Report to the European Commission on Biofuels for 2006 noted that the total sales of biofuels in the UK in 2005 were some 118 million litres, whilst total road fuel sales were approximately 49,000 million litres. As a percentage of total road fuel sales in 2005, biofuels contributed about 0.24% (DfT, 2006), and by 2007 this had increased to 1% (DfT, 2008).

The British standard for diesel (BS EN 590) permits a biofuel content of up to 5% by volume without affecting the vehicle manufacturer’s warranty. Oil companies and vehicle manufacturers have also agreed a standard (BS EN 14214) for vegetable oils suitable for blending with conventional diesel to ensure that the product meets the technical requirements of modern diesel engines[9].

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[8] http://www.dft.gov.uk/rfa/_db/_documents/Report_of_the_Gallagher_review.pdf

[9] http://www.ukpia.com/industry_issues/fuels/alternative_fuels.aspx?referrertabid=2107&linktext=Alternative+Fuels

3 Effects of fuel sulphur content on exhaust emissions

3.1 Background

DfT has stated a particular interest in the following aspects of fuel sulphur content with respect to their impacts on the emission factors used in the NAEI:

- The effects of switching form ULS fuels (50 ppm maximum sulphur content) to sulphur-free fuels (10 ppm maximum sulphur content).
- Potential 'catalyst recovery' associated with a reduction in fuel sulphur content.

Fuel sulphur has an adverse effect on emissions due to catalyst inhibition, as it competes strongly with exhaust pollutants for space on the active catalyst surface. This results in increased emissions of all regulated pollutants from catalyst-equipped petrol vehicles. However, it has been suggested that the catalyst inhibition effect may be reversible, and older catalyst-equipped vehicles switching to a lower-sulphur fuel could experience some degree of catalyst recovery resulting in reduced emissions.

The introduction of sulphur-free fuels should also enable advanced engine and exhaust after-treatment technologies - such as lean burn GDI vehicles, particle traps and regenerative NO_x storage systems - to meet increasingly stringent exhaust emissions regulations without substantially affecting fuel consumption, CO_2 emissions and long-term durability.

This Chapter of the Report reviews the literature relating to the effects of fuel sulphur content on exhaust emissions. The issues addressed are:

- Emissions from advanced technology vehicles.
- Catalyst ageing and recovery.
- Particle number emissions.

The specific questions which are of interest to DfT are addressed in a summary at the end of the Chapter.

Much of the recent work on the effects of fuel properties on vehicle emissions in Europe has been conducted by the Oil Companies' European Organisation for Environment, Health and Safety (CONCAWE), and within the EC Fifth Framework project ARTEMIS[10]. This work has been described in a number of different CONCAWE reports, and there is a degree of overlap (*e.g.* vehicles, fuels) between the reports. This ought to be apparent in the text.

It should also be noted that the refining processes involved in producing low-sulphur fuels produce more CO_2 emissions than those associated with high-sulphur fuels. The exact effects on emissions of CO_2 and other greenhouse gases depend upon a multitude of factors, and these pollutants are beyond the scope of this Report. However, it is worth mentioning that in May 2000 the European Commission issued a 'call for evidence' to evaluate the potential benefits and drawbacks of reducing the sulphur content of European road fuels below the 50 ppm limit. Dastillung *et al.* (2005) provided an update of the evidence, and predicted the CO_2 increase for refineries meeting the fuel sulphur requirement. It was estimated that a reduction in fuel sulphur content to 50 ppm equated to an additional CO_2 emission of 3.5 to 4.3 Mt/a, and a reduction to 10 ppm equated to an addition CO_2 emission of 7.3 to 9.2 Mt/a.

3.2 Emissions from advanced-technology vehicles

De Craecker *et al.* (2005) assessed the exhaust emission benefits which could achieved using advanced diesel engine and exhaust after-treatment technologies in conjunction with low-sulphur fuels, and the remaining potential for improvements in vehicle emissions through fuel quality. Three heavy-duty diesel engines and two diesel passenger cars were selected for the study. The heavy-duty engines were:

- A Euro III model employing an existing market technology.

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[10] ARTEMIS = Assessment and Reliability of Transport Emission Models and Inventory Systems.

- A prototype Euro IV model using a combined system of cooled EGR[11] and a continuously regenerating trap (CRT).
- A prototype Euro V engine using SCR[12]/urea, together with engine modifications to optimise engine-out NO_x/PM (without a particulate filter).

Details of the vehicles used in this study are shown in Appendix B. The two Euro 3 diesel cars represented the advanced technologies available on the European market in 2002:

- Car A: a medium-sized, direct-injection (DI) car with an oxidation catalyst (Car D in Appendix B).
- Car B: a large, fixed-common-rail, DI car with a diesel particulate filter (DPF) which regenerated with the aid of a fuel-borne catalyst (Car E in Appendix B).

Seven test fuels were used. These were classified as:

- Fuels D2, D3 and D4, which covered a range of sulphur levels (280 ppm, 38 ppm, 8 ppm sulphur respectively).
- D5 and D8, which were near-sulphur-free fuels (<5 ppm sulphur) with extremely low density and aromatic content - Swedish Class 1 diesel fuel and Fischer-Tropsch diesel (FTD)[13].
- D6, a diesel fuel with year 2000 sulphur levels (307 ppm) but high density and aromatic content.
- D7, a blend of fuel D4 with 5% rapeseed methyl ester (RME) (7 ppm sulphur).

The standard legislative emission test cycles for light-duty vehicles and heavy-duty engines were used during the tests, but these were supplemented by real-world cycles from the ARTEMIS project and several steady-state conditions. For the heavy-duty engines the relevant legislative test cycles (ESC and ETC[14]) were used, together with a series of extended steady-state modes covering both ‘on-cycle’ and ‘off-cycle’ measurement points. A common test sequence was used in order to obtain comparable results from different fuel/engine combinations.

As shown in Figure 1, considerable progress in the control of NO_x emissions from Euro III to Euro V engines was evident from the results. Changes in the fuel sulphur content, which decreased from fuel D2 to fuel D4, did not influence NO_x emissions. Fuel D6 gave the highest NO_x emissions for the Euro III engine, but the difference relative to fuels D2-D4 was small, as was the effect of the addition of 5% RME (D7 compared with D4). The effects of fuel sulphur content on NO_x emissions from Euro IV and Euro V engines were also relatively small. Larger effects on NO_x emissions were observed for the fuels having <5 ppm sulphur – the Swedish Class 1 fuel D5, and the FTD fuel D8, although the Euro III engine was not tested using the latter.

Figure 2 shows that the Euro IV engine with a particulate trap gave the lowest PM emissions, although PM emissions from the Euro V engine were also very low. In the case of the Euro III engine, reducing the fuel sulphur content (*e.g.* fuels D2 to D4) led to slightly reduced PM emissions. Fuels D2 and D6, which had a comparable sulphur content but differed in other properties, gave similar PM emissions. The addition of 5% RME to fuel D4 (*i.e.* fuel D7) did not affect PM emissions. Fuels D5 (Swedish Class 1) and D8 (FTD) performed similarly, and gave lower PM emissions than the other fuels. In the advanced Euro IV and Euro V engines the effects of fuel sulphur content were very small in absolute terms.

From Figure 3 it can be seen that the effects of sulphur content on NO_x emissions from the cars were not significant over the legislative cycle (NEDC[15]), although fuels D5 and D8 again gave lowest NO_x emissions for car B. Under the higher speed, load and temperature conditions of the ARTEMIS motorway cycle (not shown) NO_x emissions roughly doubled for both cars, and fuels D5 and D8 gave significant - but still rather small - reductions in NO_x emissions from car B, though not from car A.

Car A, although certified to the Euro 3 standard, produced PM emissions close to the Euro 4 limit (Figure 4). For this car the results of fuel sulphur content appear to have been mixed - fuel D6 gave the highest PM emissions, whereas fuels D5 and D8 gave the lowest emissions, but fuels D2 to D4 resulted in similar emission levels. The addition of 5% RME to D4 did not significantly affect PM emissions.

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[11] EGR = exhaust gas recirculation.

[12] SCR = selective catalytic reduction.

[13] Fischer-Tropsch diesel is a premium diesel product with a very high cetane number (75) and zero sulphur content. FTD is generally produced from natural gas.

[14] European Transient Cycle.

[15] New European Driving Cycle.

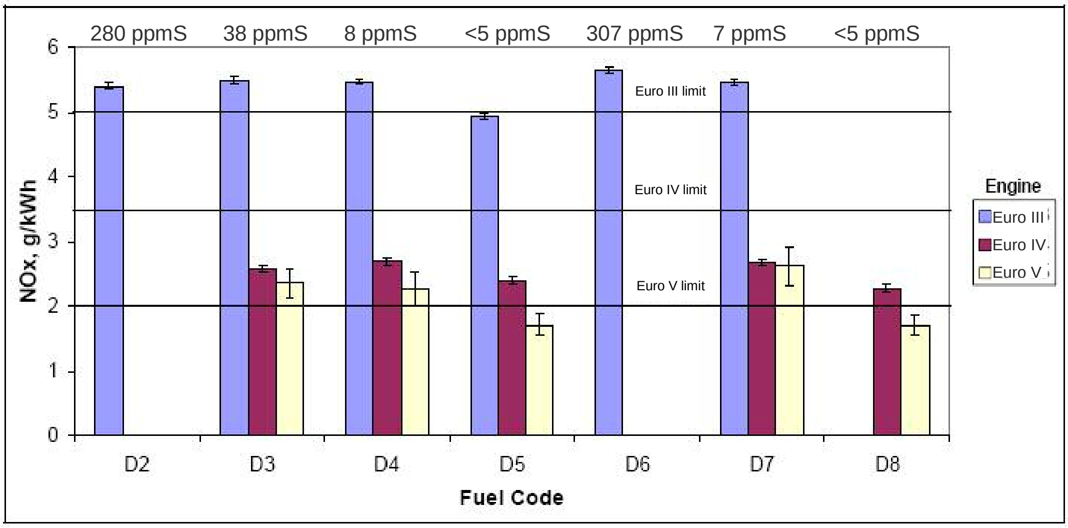

Figure 1: NO_x emissions from heavy-duty engines over the ETC cycle (De Craecker *et al.*, 2005).

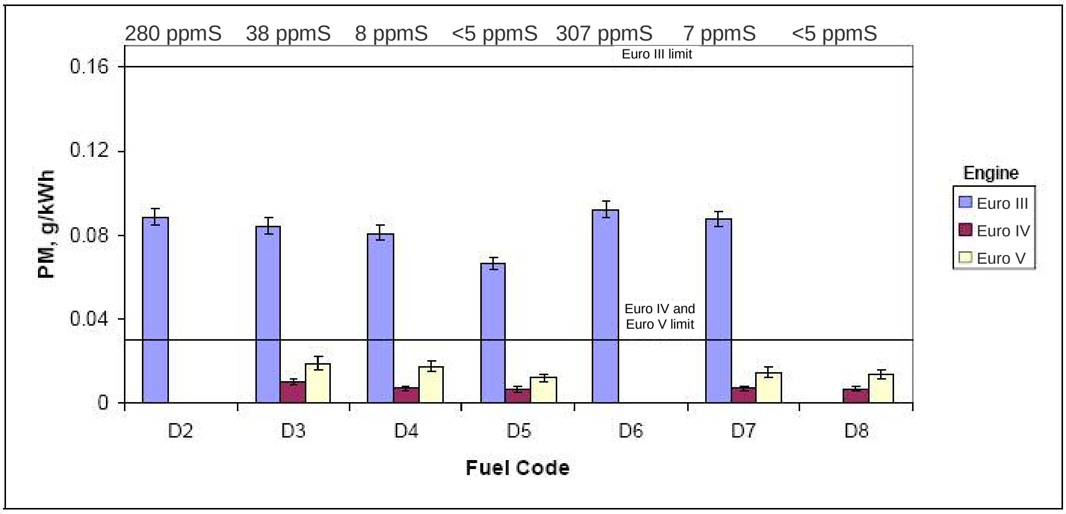

Figure 2: PM emissions from heavy-duty engines over the ETC Cycle (De Craecker *et al.*, 2005).

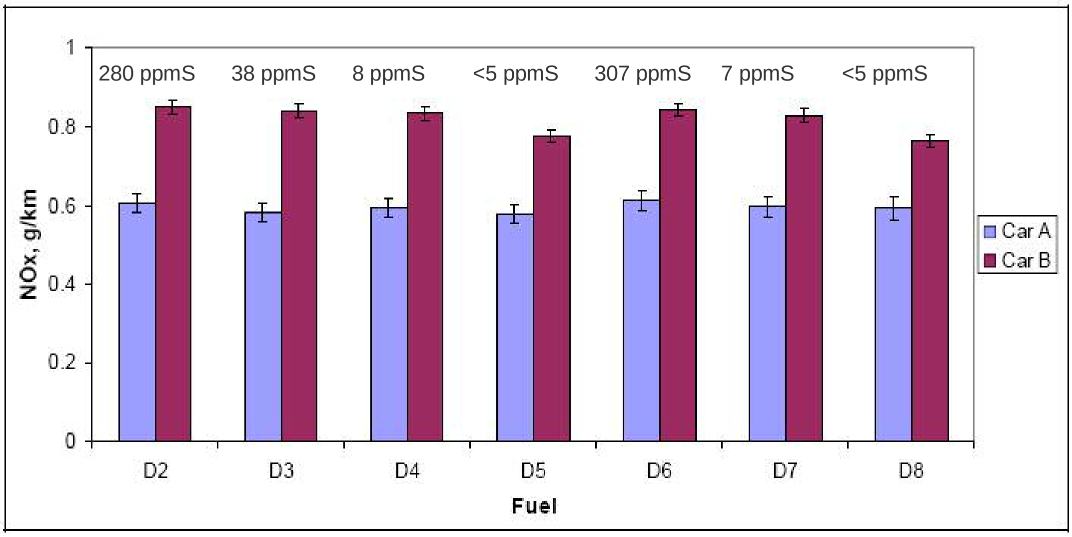

Figure 3: NO_x emissions from diesel cars over the NEDC (De Craecker *et al.*, 2005).

A more striking effect was that of the DPF. Car B produced extremely low PM emissions - less than 10% of the Euro 4 limit for all fuels - due to the DPF. In this car, the differences between fuels on PM emissions over the NEDC were not significant. Over the ARTEMIS motorway cycle a stronger effect of fuel sulphur content was evident (Figure 5). For both cars the 300 ppm sulphur fuels (D2 and D6) showed significantly higher PM emissions than the other fuels. Fuels D5 and D8 showed further benefits over the other fuels for car A, but not for car B, as the PM emissions with this DPF-equipped car were already very low for all fuels with less than 50 ppm sulphur.

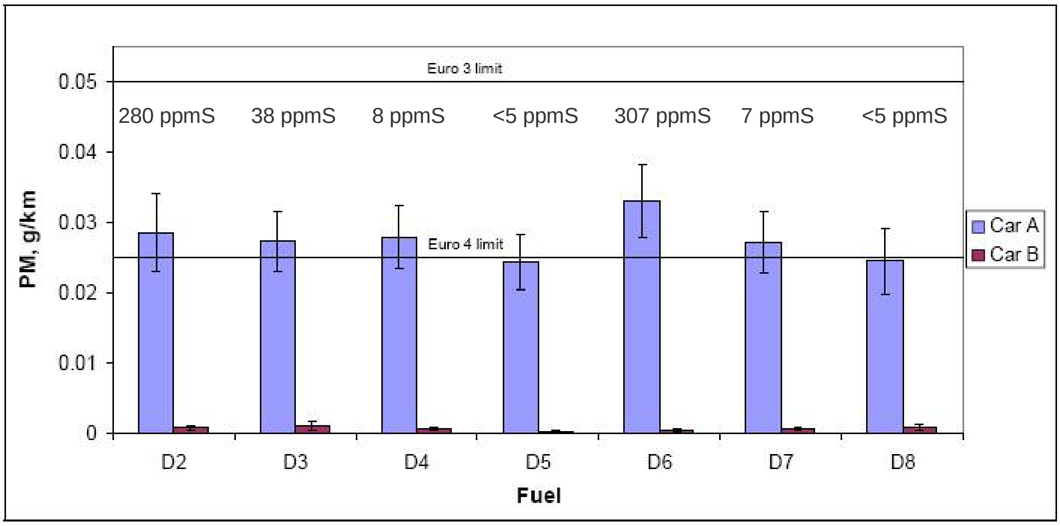

Figure 4: PM emissions from diesel cars over the NEDC (De Craecker *et al.*, 2005).

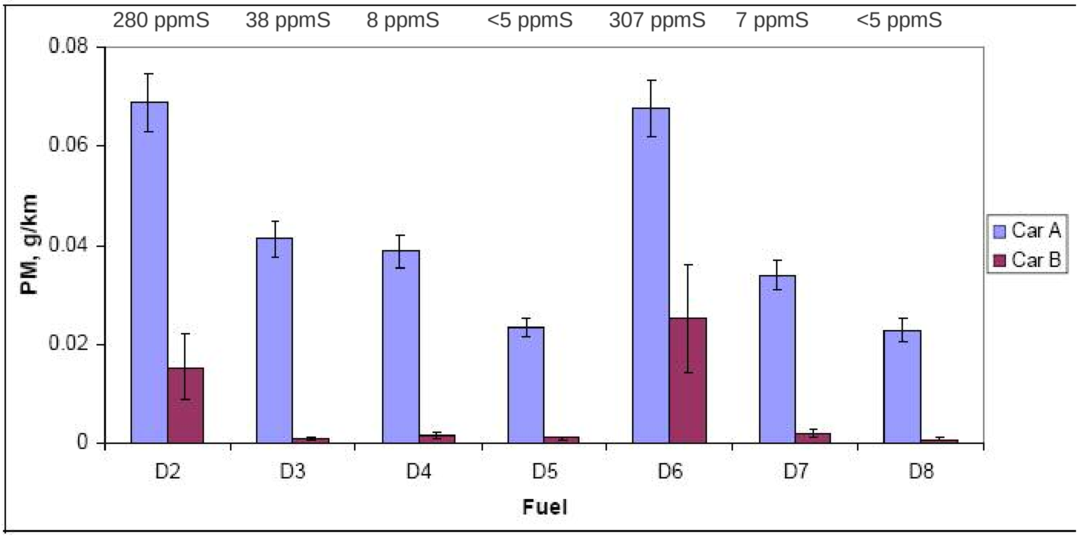

Figure 5: PM emissions from diesel cars over the ARTEMIS Motorway cycle (De Craecker *et al.*, 2005).

HC and CO emissions from the advanced diesel engines and vehicles were very low, and well below the prescribed emissions limits. Diesel fuels with higher hydrogen:carbon ratios gave lower engine or vehicle CO_2 emissions, although overall effects would need to be considered on a ‘well-to-wheel’ basis. These fuels also gave higher volumetric fuel consumption and lower maximum power due to their lower density. Despite the wide range of fuels tested, the engine/vehicle energy efficiency was not sensitive to fuel changes, and no statistically significant differences between fuels were seen.

The application of SCR/urea to control NO_x in the prototype Euro V engine, with the engine tuned for better efficiency, improved fuel efficiency by about 5% compared with the Euro III engine. Conversely, the use of EGR plus CRT to achieve Euro IV heavy-duty emissions limits resulted in a loss in engine efficiency compared with the Euro III engine.

3.3 Catalyst ageing and recovery

As a catalyst ages there is a reduction in its active surface area and oxygen storage capacity. It is possible for sulphur to deactivate a considerable portion of the surface area and oxygen storage. For older technology vehicles with fresh or aged catalysts, AECC (2000) found that most studies have shown that lower fuel sulphur levels lead to lower emissions. AECC also noted that the reversal of sulphur adsorption is problematic, as a complex control system is required and there is the possibility of increased emissions of H_2S and SO_2.

Laboratory experiments have shown that high temperatures are generally needed to remove sulphur from both the surface of the catalyst and from the washcoat matrix. In addition, a rich exhaust or an alternating sequence of rich and lean exhaust is often needed. Under the correct conditions the sulphur impact can be fully reversed (SENCO, 2000).

The potential reversibility of the sulphur effect could have important implications for a sulphur-control programme. If the effects are irreversible it becomes important that all the fuel a vehicle uses during its lifetime contains low levels of sulphur. If, on the other hand, the sulphur effect were fully reversible under normal driving conditions, it would be possible to limit the availability of low-sulphur fuel to where and when it is most needed. This could have important consequences regarding both the cost of producing the fuel and the CO_2 emissions from refineries (SENCO, 2000).

The impact of ageing on catalyst performance – including the effects of fuel sulphur content – has been investigated more recently in a number of US studies. Following a review of these studies, Rickeard *et al.* (2003) concluded that:

- Fleet average results were influenced by a number of sensitive vehicles.
- Catalysts that had been aged for 100,000 miles showed increased sensitivity to sulphur, especially for NO_x emissions.
- The lowest emitting vehicles were not necessarily the most sensitive to sulphur.

However, additional tests on two European Euro 3 petrol vehicles carried out by CRC in cooperation with CONCAWE showed no evidence of increased sulphur sensitivity after catalyst ageing (Figure 6).

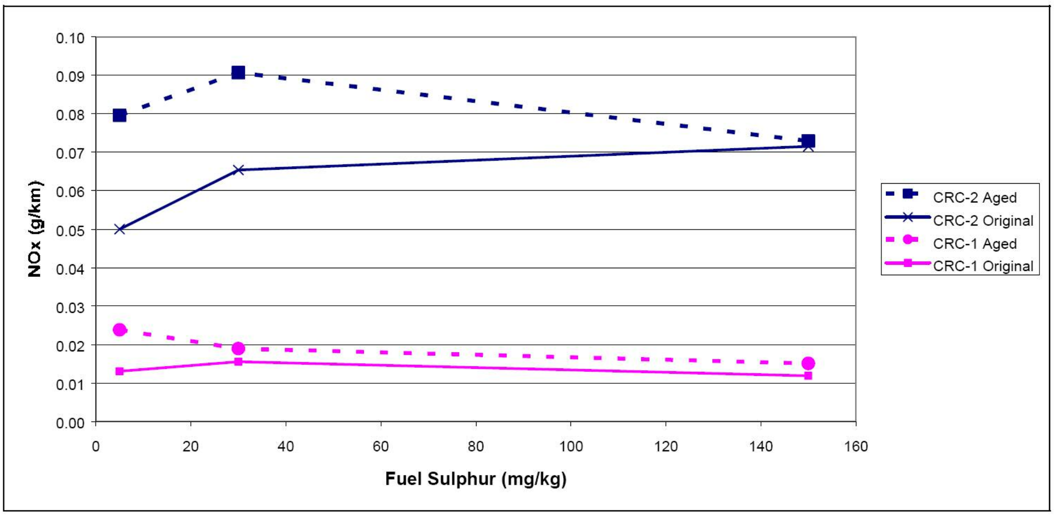

Figure 6: Response of NO_x emissions from two Euro 3 petrol vehicles to fuel sulphur content (NEDC) (Rickeard *et al*., 2003).

Rickeard *et al*. (2003*)* also examined the short-term sensitivity of four petrol cars to fuel sulphur content over a range from 4 ppm to 150 ppm. Two of the test vehicles were certified to the Euro 3 standard, and two were certified to the Euro 4 standard. In all cases the measured exhaust emissions were found to be well within the respective certification limits. Again, the emissions from all four vehicles showed little or no sensitivity to fuel sulphur content for any of the measured compounds (regulated pollutants and CO_2). It was concluded that:

- Low emissions can be achieved without significant short-term sensitivity to fuel sulphur.
- There is no evidence of a non-linear response to sulphur at levels up to 150 ppm.

- Fuel sulphur sensitivity is influenced by catalyst system design rather than by emissions level.
- Reductions in fuel sulphur content from 150 ppm to 10 ppm seem unlikely to bring substantial emissions benefits for current Euro 3 and 4 vehicle technologies.

3.4 Particulate number emissions

Particle emissions from vehicles have generally been controlled via legislation based on mass. However, recent studies have indicated that adverse health effects may not only be dependent on total particulate mass, but on other metrics including size, number and surface area.

Where significant amounts of carbon particulate are emitted in the exhaust, volatile sulphates and hydrocarbons tend to condense onto the existing particles. However, under conditions where carbon particle emissions are reduced there is also a tendency for hydrocarbons, and particularly sulphates, to condense independently, forming large numbers of very small ‘nucleation mode’ particles. The extent of this nucleation mode formation has been shown to be dependent upon engine type and fuel composition, the use of after-treatment, the vehicle operating conditions, and also the sampling and measurement conditions.

Carbone *et al.* (2005) examined the effects of fuel composition on particle emissions from advanced engines and vehicles. The work was carried out as part of the European Commission Fifth Framework project PARTICULATES. The vehicles tested were the same as those reported by De Craecker *et al.* (2005) (see Section 3.1.1), plus two Euro 3 petrol direct-injection vehicles: one stoichiometric equipped with a three-way catalyst (TWC), and another using a lean mixture, a TWC and a NO_x trap. The same diesel and petrol fuels were used as in the study by De Craecker *et al.* (2005).

This study showed that low-sulphur fuels allow DPFs to reduce particulate mass emissions by more than an order of magnitude, and the number of particle emissions by several orders of magnitude. A prototype Euro V engine with NO_x reduction by SCR but without a particulate filter was shown to reduce particulate mass emissions but to have less impact on particle number emissions. The effect of diesel fuel sulphur was greatest under high-temperature operation. Under these conditions, fuels with 50 ppm or lower sulphur reduced particle mass and number emissions. In absolute terms, the effects of changes in fuel parameters other than sulphur were small with the advanced engine technologies. There was no clear short-term effect of petrol sulphur content on particulate emissions from direct-injection petrol vehicles.

3.5 Summary

The main points which have been drawn from this Chapter are summarised below.

3.5.1 Effects of change in fuel sulphur content from 50 ppm to 10 ppm

Large reductions in exhaust emissions have been demonstrated with advanced engine and after-treatment technologies in combination with low-sulphur fuels. However, within a given Euro class the effects of fuel sulphur content on NO_x and PM emissions are generally either not significant or rather small. Reductions in fuel sulphur content from 50 ppm to 10 ppm seem unlikely to bring substantial emissions benefits for Euro 3/III and 4/IV vehicle technologies. The main exception may be PM emissions over high-load cycles.

For heavy-duty diesel engines:

- Changes in fuel sulphur content (50 ppm to <10 ppm) within a Euro class (III, IV, V) have not been shown to influence NO_x emissions.
- For Euro III engines reducing the fuel sulphur content leads to a slight reduction in PM emissions (up to around 10%).

For diesel cars:

- The effects of sulphur content on NO_x emissions are not significant over the NEDC, though may become significant over driving cycles which result in higher engine loads.
- For Euro 3 vehicles, there is a reduction in PM from 300 ppm sulphur to 50 ppm sulphur, but little further reduction at sulphur levels of 7-8 ppm. However, there does appear to be a further reduction in PM at sulphur levels of less than 5 ppm.

- PM emissions are dramatically reduced for vehicles equipped with diesel particulate filters. In such cases, the differences between fuels over the NEDC are not significant. Over the ARTEMIS motorway cycle, a stronger effect of fuel sulphur content has been observed. The 300 ppm sulphur fuels showed significantly higher PM emissions than the other fuels, but PM emissions were very low for all fuels with a sulphur content of less than 50 ppm.

3.5.2 Catalyst recovery

Emissions from modern petrol Euro 3 and Euro 4 cars do not appear to show a change in sensitivity to fuel sulphur level with age. It is possible that older petrol vehicles could show some degree of catalyst recovery (*i.e*. lower emission levels) when used on sulphur-free fuel. However, such recovery is rather difficult to quantify as there seems to be little interest in testing old vehicles on new fuels.

4 Effects of other fuel properties on exhaust emissions

In this Chapter of the Report a brief review is presented of the effects of varying other fuel properties on emissions. The fuel properties which are covered are aromatic content, cetane number and 'other properties'.

4.1 Aromatic content

The effects on emissions of fuel aromatic content were examined by Cuvelier *et al.* (2002). The tests were conducted on three cars and two heavy-duty engines, representing a range of typical Euro 3/III technologies. One of the cars was equipped with common-rail injection, one with unit injectors, and one with an advanced rotary pump. The cars therefore reflected the most advanced engine technologies available at the time. One of the heavy-duty engines had a capacity of 7.3 litres and was equipped with an in-line pump but not exhaust gas recirculation (EGR). The other engine had a capacity of 10.6 litres, and was equipped with unit injectors and cooled EGR. The Euro 3 Motor Vehicle Emission Group (MVEG) test cycle was used to test the cars, and the European Stationary (steady-state) Cycle (ESC) test was used for the heavy-duty engines. Fuel effects were generally found to be small compared with engine technology effects and between-test variability, and significant fuel effects were difficult to identify. For the cars, the effects of changing the fuel aromatic content varied between vehicles. Only one vehicle showed significant effects on PM and NO_x; in this case NO_x emissions decreased and PM emissions increased as aromatics were reduced. There were no consistent trends in HC emissions, but CO emissions tended to decrease with lower aromatic content. As the total aromatics effects were small, it was not possible to quantify separately the relative contributions from mono-aromatics versus poly-aromatics. In the case of the heavy-duty engines, reducing the aromatic content of the fuel reduced HC emissions but had no significant effect on PM, NO_x or CO.

EPEFE showed that for light-duty vehicles reducing polyaromatics decreased NO_x, PM, formaldehyde and acetaldehyde emissions, but increased hydrocarbon, benzene and CO emissions. For heavy-duty vehicles, reducing polyaromatics decreased NO_x, particles and hydrocarbon emissions (Hublin *et al*., 1996).

Doel *et al.* (2005) examined the relationships between fuel composition and exhaust emissions of PAHs from a range of vehicles and fuels. The testing was separated into two phases. Phase 1 of the experiment consisted of tests on Euro 1 and 2 diesel cars, and a Euro II heavy-duty diesel engine. A 1994 heavy-duty engine was also tested during Phase 1. This engine had an emissions performance close to the Euro II standard, and was considered to be typical of the bulk of the European Euro II heavy-duty diesel fleet. Phase 2 consisted of tests on Euro 3 and Euro 4 cars. Again, the vehicles used in this study are those shown in Appendix B. The cars and heavy-duty engines were tested over the NEDC and ECE49 cycles respectively. Five diesel fuels were used in Phase 1. These had a PAH concentration of between <1% and 12% by mass. Five more diesel fuels were also used for the Phase 2 tests, with a PAH concentration of between <1% and 9% by mass. Two petrol fuels were used in Phase 1, with benzene content of 0.17% and 1.59%. These were produced by blending fuels to produce a range of aromatic and sulphur content, but were both within the specification limits of EN228. In Phase 2 a single petrol fuel with a benzene content of 0.09% was used. This was considered to be representative of the 50 ppm sulphur EN228 grade required from 2005.

Figure 7 shows the emissions of '2+ ring' PAHs by vehicle. Figure 8 shows the average 2+ ring PAH emission values plotted against the fuel poly-aromatic content using seven of the fuels. The older diesel vehicles produced higher PAH emissions and were also more sensitive to fuel composition than the newer, or more advanced, diesel vehicles. PAH levels from both Vehicle D (unit injectors/oxidation catalyst) and Vehicle E (common rail/particulate filter) were insignificant compared with emissions from the vehicles using older technologies. The TWC-equipped petrol vehicles produced far lower 2+ ring PAH emissions than the diesels vehicles. Vehicle Y, which was equipped with variable valve timing, was the lowest emitting petrol car. The older technology vehicles gave an approximately linear increase in 2+ ring PAH emissions with increasing diesel fuel poly-aromatic content. Similar results were observed for the Euro II heavy-duty diesel engine. Diesel vehicles with after-treatment were not sensitive to the fuel aromatic content, although the emission levels were very low. The other conclusions from this study were that increasing fuel mono-aromatics content increases 2+ ring PAH emissions, but poly-aromatic content was found to have a greater effect. However, reducing diesel fuel poly-aromatics, even to zero, would not eliminate exhaust PAH emissions, as a significant proportion is combustion-derived.

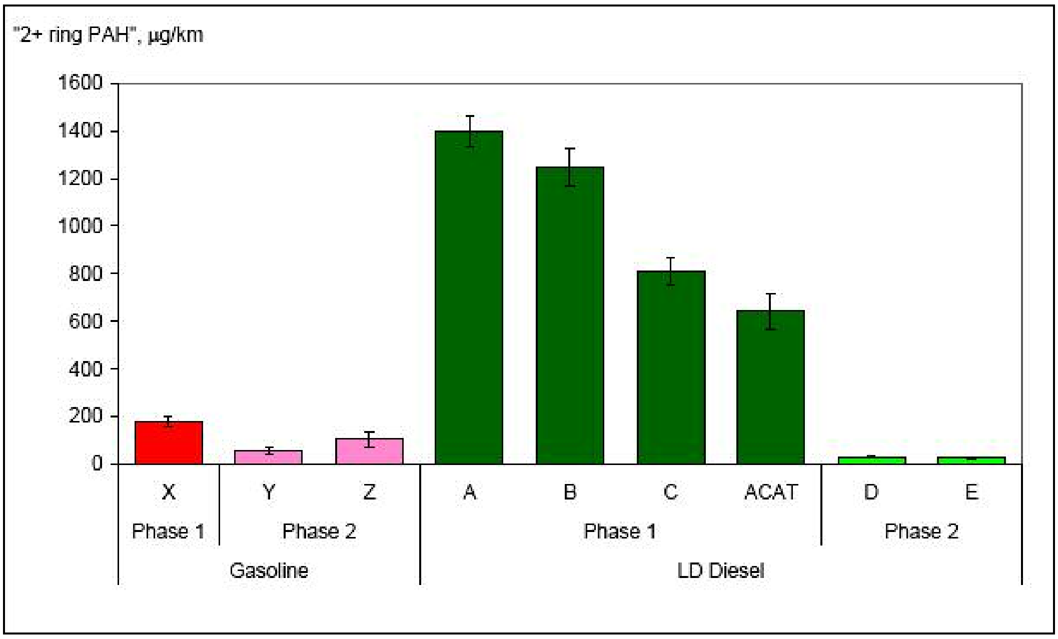

Figure 7: Emissions of 2+ ring PAHs by vehicle type (Doel *et al.*, 2005).

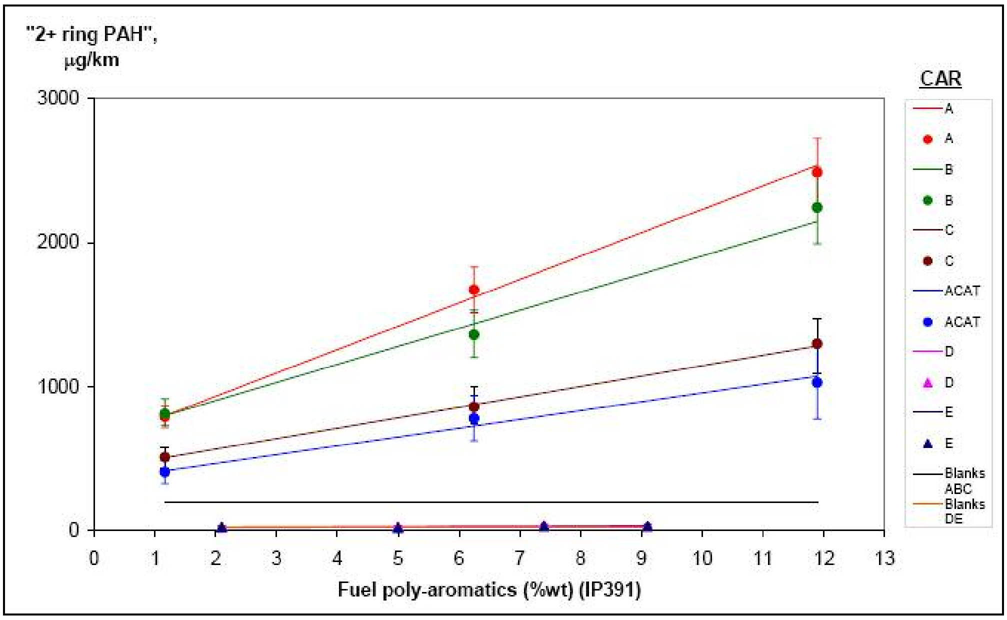

Figure 8: Emissions of 2+ ring PAHs as a function of fuel poly-aromatic content (legend refers to Appendix B) (Doel *et al.*, 2005).

4.2 Cetane number

High-cetane-number fuels enable an engine to be started more easily at lower air temperatures, reduce white smoke exhaust, and reduce diesel knock. An increase in cetane number also generally results in a decrease in emissions of CO, HC and NO_x (most notably in heavy-duty engines), as well as emissions of benzene, 1,3-butadiene, formaldehyde and acetaldehyde from light-duty vehicles. For diesel vehicles equipped with oxidation catalysts or catalysed PM filters, emissions of CO, HC, benzene, 1,3-butadiene, formaldehyde and acetaldehyde will tend to be less sensitive to cetane number. Whilst one major study (EPEFE) found that particle emissions increased from light-duty vehicles as the cetane number increased (no significant effect was seen in heavy-duty engines), other research has suggested that an increase in cetane number can lead to lower particle emissions (Walsh, 2004).

Cuvelier *et al.* (2002) also examined the effect of cetane number on emissions from the vehicles and engines described in the first paragraph of Section 4.1. Increasing the Cetane Number (from 53 to 58) had no significant effect on NO_x or PM emissions from either the cars or the heavy-duty engines tested, but it did reduce CO and HC emissions (although the reductions were not always significant). No differences in emissions were observed between natural cetane fuels and those in which the cetane number was boosted using ignition-improving additives.

4.3 Other properties

Stradling *et al.* (2004*)* examined the effects of aromatic content, olefin content and volatility on emissions from modern petrol vehicles. The study examined the following changes in fuel properties:

- A reduction in olefin content from 14% to 5% by volume.
- A reduction in aromatic content from 38% to 26% by volume.
- A reduction in E70[16] from 38 to 22% by volume.
- A reduction in final boiling point (FBP) from 197 to 176°C.

Four cars were used, with the following technologies

- Stoichiometric DI, TWC Euro 3.
- Variable valve actuation, multipoint-injection(MPI), TWC Euro 4.
- Lean DI, TWC + NO_x trap, Euro 3.
- Lean DI, TWC + NO_x trap, Euro 4.

Emissions from the test vehicles were all very low, and in compliance with the appropriate Euro 3 or Euro 4 limits. The measured effects of fuel changes on the emissions of regulated pollutants (NO_x, HC and CO) were small, and often conflicting, with differing directional responses for different vehicles and pollutants. The main findings were:

- A reduction in fuel volatility, representing the combined effects of vapour pressure, E70 (38% by volume to 22% by volume) and E100, had no consistent effect on NO_x emissions, increased HC across all vehicle technologies (10%), but decreased CO emissions from two cars.
- A reduction in FBP from 197ºC to 176ºC increased NO_x emissions from one car, but had no significant effect on emissions from the others. HC emissions were reduced by 9%, and CO emissions increased by 20%, with significant effects in both cases for two cars.
- A reduction in aromatic content from 38% by volume to 26% by volume showed conflicting effects, increasing NO_x emissions from two cars and decreasing emissions from the others, but the effects were significant for only one vehicle. Reducing the aromatic content increased HC emissions from the two lean DI cars but showed the opposite effect in the MPI car.
- A reduction in olefin content from 14% by volume to 5% by volume gave no significant improvement in NO_x, HC or CO emissions in any of the cars.
- The stoichiometric and lean DI vehicles showed a similar response in PM emissions to changes in fuel quality. Lowering FBP and lowering olefins content gave a reduction in PM emissions, whereas lowering aromatic content and volatility showed no significant benefits. PM emissions from the advanced MPI car were very low on all fuels tested and insensitive to fuel changes.

In the ARTEMIS project, the effects of fuel specification emissions from LDVs, HDVs and two-wheel vehicles were investigated and the main findings are described below.

In the LDV work, eight different fuels were used: three Euro 3 petrol fuels (from Austria, France and Greece), three Euro 3 diesel fuels (from Finland, Italy and France), one Euro 4 petrol fuel and one Euro 4 diesel fuel. This matrix of fuels was tested for three different driving cycles: the cold-start NEDC, the cold-start ARTEMIS urban cycle and the full ARTEMIS cycle (urban, rural and motorway phases). The programme was performed using two Euro 3 vehicles: one petrol car with multi-point injection, and one diesel car. Although it was thought that fuel composition had a certain influence on emissions, the variability in data was high and a

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[16] E70 and E100 are measures of how much of the fuel volume has evaporated at these three different temperatures on the distillation curve.

limited vehicle sample size was used. Consequently, no statistically significant relationships were observed between any fuel properties and emissions. Therefore, no corrections to emission factors were proposed for the effects of fuel properties on emissions (Joumard *et al*., 2006). In the PARTICULATES project (which was clustered with ARTEMIS), a dedicated sampling and measurement system was employed in several laboratories in order to characterize the particle emissions of light-duty vehicles of various technologies, and using several fuels and a number of test cycles (Samaras *et al.*, 2005). The only significant fuel effect observed was that of sulphur on the total particle number and particle surface area of diesel vehicles.

For heavy-duty vehicles, fuel effects in ARTEMIS were based upon a review of various measurement programmes, such as EPEFE and the USEPA Heavy-Duty Engine Working Group Programme (Rexeis *et al*., 2005 and references therein). The ARTEMIS approach is described later in this Report.

Five motorcycles were tested in ARTEMIS to address the effects on emissions of fuel properties. The vehicles had a wide range of engine capacity and physical dimensions, but none of them was equipped with an exhaust after-treatment system. The motorcycles were tested over seven driving cycles and two different fuels - one fuel which met existing requirements and another which complied with near-future requirements. Hungarian market fuel was selected as the ‘current’ fuel. The future fuel met the requirements laid down for Category 4 in the World Wide Fuel Charter (WWFC[17]) (WWFC, 2002). The principal differences between these fuels were sulphur content (23 ppm for Hungarian market and 3.4 ppm for WWFC4 fuel), olefins (11.2 against 0.4 vol%), aromatics (31.9 versus 26.5 vol%) and oxygen content (0.58 against 1.74 vol%). The results of the fuel property tests were summarised in a detailed report by Kis *et al*. (2005). The main conclusions were as follows:

- For all motorcycles CO emissions were, on average, 15% lower when using the WWFC4 fuel instead of the Hungarian market fuel. The effect was highest during the EUDC test cycle, and the trends were similar for two-stroke and four-stroke engines.
- For HC the WWFC4 fuel generally resulted in slightly lower emissions. Similar trends were observed for two-stroke and four-stroke engines.
- For three of the five motorcycles tested, NO_x emissions increased by 10-20% when the WWFC4 fuel was used. NO_x emissions from the two-stroke motorcycle tested decreased by around 15%.
- Most of the motorcycles showed a significant increase (around 4%) in exhaust CO_2 emissions when they were tested using the WWFC4 fuel. No differences were observed between two-stroke and four-stroke engines. Fuel consumption was not affected by the change of fuel.

A likely explanation for these results might be that the additional oxygen in the WWFC4 fuel reacted with CO and HC and was converted into CO_2. However, it is not clear whether only the oxygen content was responsible for this effect or if other properties also affected emissions.

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[17] The World Wide Fuel Charter is a joint effort by European, American and Japanese automobile manufacturers and other related associations, and recommends global standards for fuel quality, taking into account the status of emission technologies. Category 4 fuels will be applied in future vehicles which will meet very stringent emission limits.

5 Biofuels

The need to reduce greenhouse gas (GHG) emissions has accelerated efforts to increase the use of non-fossil fuels in road transport, as reflected in the Biofuels Directive and the RTFO. Many different biofuels and fossil-biofuel blends are available. The effects on exhaust emissions of two main types of biofuel are reviewed in this Chapter of the Report: biodiesel blends and ethanol blends. These are the main biofuels available in the UK. However, an extensive review could not be conducted in the project, and it is recognised that the information presented is rather limited in scope.

5.1 Biodiesel blends

Renewable diesel fuel substitutes which are produced from rapeseed, soybean, sunflower, palm and other vegetable oils are known collectively as biodiesel, and this is the most common biofuel in Europe. Its chemical name is fatty acid methyl (or ethyl) ester (FAME). In Europe, the main source of biodiesel is rapeseed, whereas in the US the most common source is soybean. Biodiesels have long been used as fuel for diesel engines - they have similar properties to conventional petroleum diesel fuel, for which they can be substituted with little or no engine modification.

Biodiesels have zero sulphur content and relatively high cetane numbers. Due to their renewable character, GHG emission reduction potential, and a generally favourable life-cycle analysis, they are an attractive alternative to petroleum diesel fuel. The production of biodiesel can also result in substantially less pollutant emissions and waste by-products. However, as production methods and sources of biodiesel vary greatly, there is a large range in the CO_2 emissions per amount of fuel produced (Blumberg *et al.*, 2003; Majewski and Jääskeläinen, 2005).

Due to concerns about the potential cost, the need for fuel system modification, and damage to engine components, a common approach has been to blend biodiesel with petroleum diesel. The most common blend in the US has been 20% biodiesel and 80% petroleum diesel, sometimes referred to as B20 (under the same convention, ‘pure’ biodiesel is termed B100). In Europe biodiesel is predominantly used either as low blends (B5 or less) or as B100. Blends of up to 5% biodiesel are broadly accepted for use in existing diesel engines by engine and fuel injection equipment manufacturers (Majewski and Jääskeläinen, 2005).

The effects of biodiesel on exhaust emissions have been reviewed extensively elsewhere (*e.g.* Majewski and Jääskeläinen, 2005). The findings of these reviews are briefly summarised in this Section.

Regulated emissions of biodiesel blends have been studied in some detail. However, the results of these studies have often been inconclusive or contradictory, making it difficult to quantify trends (Majewski and Jääskeläinen, 2005). The observed scatter in the data may be attributed a number of factors, including variability in the properties of various biodiesel fuels (especially in the cetane number), as well as the properties of the petroleum blending stock. Studies have also been conducted on different types of engine and using different test cycles. Furthermore, relative emission effects reported with biodiesel may be distorted due to the use of different baseline fuels. For a valid emission comparison, engines should be recalibrated to their original power output to account for the lower heating value of biodiesel - a requirement that is often neglected. Optimal utilisation of biodiesel would also require that the engine combustion process be specifically adjusted for the test fuel. In practice, studies of biodiesels have been conducted using engines which were designed and calibrated for petroleum diesel fuels. If engines were specifically calibrated for biodiesel, higher emission benefits could possible (Majewski and Jääskeläinen, 2005). The exact effects of biodiesel on greenhouse gas emissions depend upon multitude of other assumptions, which still remain to be determined (Majewski and Jääskeläinen, 2005). These effects are beyond the scope of this Report.

A comprehensive summary of biodiesel emission effects was conducted by the USEPA (2002). The measurements were conducted over the FTP using commercial (although pre-1998) heavy-duty engines and commercial fuels. Figure 9 illustrates the relationships between the percentage emission impact and the biodiesel content in the blend. Biodiesel and its blends generally reduce emissions of most pollutants from diesel engines. The only regulated pollutant that has been shown to consistently increase with biodiesel content is NO_x.

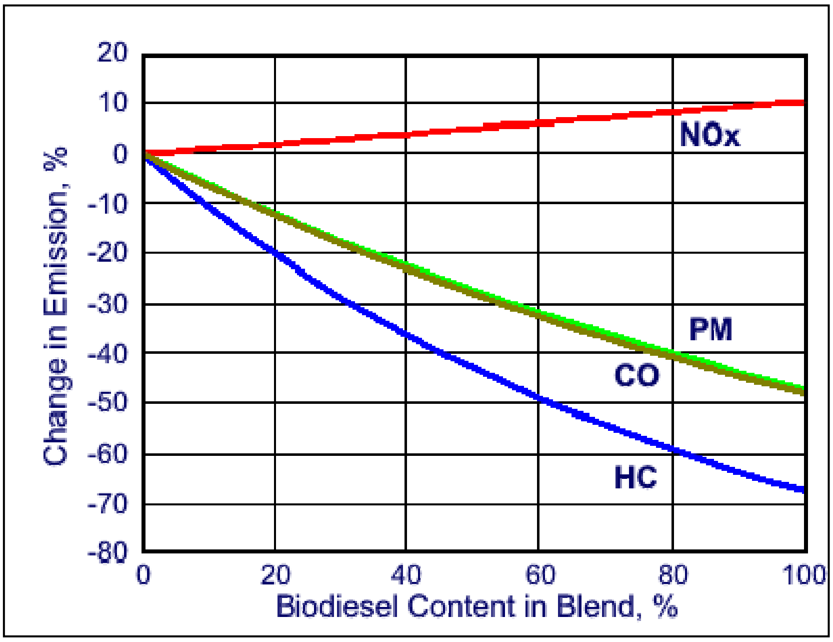

Figure 9: Average impact of biodiesel on emissions from heavy-duty engines (US pre-1998 technology engines, FTP transient test).

It was concluded by Majewski and Jääskeläinen (2005) that NO_x emissions with biodiesel appear to increase by typically around 10-15%. The NO_x effect depends upon the type of biodiesel feedstock; the highest NO_x emissions were reported for the most highly unsaturated fuels (soybean, rapeseed, and soapstock-based). The NO_x increase also depends on the engine technology; the NO_x increase effect appears to be higher in modern engines. It is likely that increased NO_x is caused, at least in part, by the physical properties of biodiesel which can influence the performance of fuel injection equipment, rather than by chemical effects.

There is a general agreement in the literature that biodiesel and its blends decrease exhaust emissions of CO and HC (Majewski and Jääskeläinen, 2005; Shi *et al.*, 2005; Ali *et al.* 1995). This effect is attributed to the oxygen content in biodiesel, which enables more complete oxidation in the engine cylinder. The magnitude of the reduction varies.

Several studies have shown that the use of biodiesel tends to result in reduced PM emissions (Bünger *et al.* 2000; Sharp *et al.*, 2000a). The effect of biodiesel on PM depends on the composition of diesel particulates, and it is specific to the engine and the test cycle (Majewski and Jääskeläinen, 2005). Substantial reductions in PM emissions have been shown to be possible through the addition of biodiesel to diesel fuel. B20 (a mixture of 20% biodiesel and 80% petroleum diesel) has become one of the most popular biodiesel fuel blends, and this blend has been studied in different countries (Durbin and Norbeck, 2002; Lee *et al.*, 2004). The USEPA analysis (Figure 9) found that PM emissions were reduced by 12% using the B20 blend, and by 47% using B100.

Emissions of PAHs and nitro-PAHs have been found by most authors to be significantly lower than those observed with petroleum diesel for both light- and heavy-duty engines and different test cycles (Sharp, 1998; Sharp *et al*., 2000b – cited in Majewski and Jääskeläinen, 2005). Biodiesel emissions of aldehydes and ketones depend on the type of engine and test cycle; both decreases and increases relative to petroleum diesel have been reported.

The USEPA analysis also looked into the biodiesel effect on several substances classified as toxic air pollutants, including formaldehyde, acetaldehyde, benzene, 1,3-butadiene, n-hexane, toluene, and others. In some cases (aldehydes, naphthalene, ethylbenzene, xylene) statistically significant reductions were determined with increasing biodiesel content. The magnitude of the emission reduction, however, was considerably smaller than the HC effect. In other cases, no clear emission trends could be found (USEPA, 2002).

5.2 Ethanol blends

Ethanol was first suggested as an automotive fuel in USA in the 1930s, but was widely used only after 1970. Nowadays, ethanol is used as fuel, mainly in Brazil, or as a petrol additive for octane enhancement and better combustion, mainly in USA and Canada.

The vast majority of ethanol for use as fuel is produced by fermentation, when certain species of yeast metabolise sugar (typically cane sugar) in the absence of oxygen. In order for ethanol to be suitable for use as a replacement for petrol in its pure form, it must be distilled to at least 70-80% purity by volume. Pure ethanol has a lower energy content than petrol (about 30% less energy per unit volume). Although ethanol can be used in its pure form as a fuel, in most countries it is most commonly blended with diesel or petrol, and indeed many major car manufacturers specify a limit on the ethanol content of the fuel in vehicle warranties. When ethanol is used as an additive to petrol almost all water must be removed, otherwise it will separate from the mixture and settle to the bottom of the fuel tank. This will cause the fuel pump to draw water into the engine, which will in turn cause the engine to stall.

5.2.1 Diesel-ethanol

The use of ethanol in diesel fuel can yield significant reductions in particulate matter (PM) emissions (*e.g.* He *et al*., 2003). However, there are many technical barriers to the direct use of ethanol in diesel fuel due to the properties of ethanol, including its low cetane number and the poor solubility of ethanol in diesel fuel in cold weather. In fact, diesel engines cannot operate normally on ethanol–diesel blends without special additives (McCormick and Parish, 2001).

Ali *et al.* (1995) and Shi *et al.* (2005) found that PM emissions were substantially reduced for bioethanol–diesel in comparison with petroleum diesel. Shi *et al*., 2006 described the emission characteristics of an oxygenated diesel fuel blend (bioethanol-diesel) for a Cummins-4B diesel engine. The diesel fuel blend consisted of ethanol, methyl soyate and petroleum diesel fuel. The blend ratio used in this study was 5:20:75 (ethanol: methyl soyate: diesel fuel) by volume. The engine showed a significant reduction in PM emissions, and 2-14% increase of NO_x emissions, when running on bioethanol-diesel. The change in CO emissions was not conclusive and was dependent upon the operating conditions. HC emissions from bioethanol-diesel were lower than those from petroleum diesel fuel under most test conditions. Formaldehyde, acetaldehyde, propionaldehyde and acetone in the exhaust were also measured, and the results indicated that use of bioethanol-diesel led to a slight increase of acetaldehyde, propionaldehyde and acetone emissions. A small amount of ethanol was also detected in the exhaust from burning bioethanol-diesel.

5.2.2 Petrol-ethanol

Most modern petrol cars will run on a 10% mixture of ethanol to petrol, although warranties may state that a mix of 5% is the maximum allowed. Some major car manufacturers have developed cars which run on fuels containing higher proportions of alcohol, typically E85.

In the UK in 2005, tax concessions for ethanol encouraged a minor shift and a 5% ethanol mixture entered the retail market, the ethanol source being Brazilian sugar cane. However, at the moment bioethanol blended with petrol is still only available in the UK at a limited number of outlets[18].

Poulopoulos *et al.* (2001) examined the effects of ethanol addition to unleaded petrol on emissions of regulated and unregulated exhaust pollutants. The addition of ethanol up to 10% by mass resulted in a decrease in CO emissions across the whole operating range. Engine-out emissions of acetaldehyde were significantly increased for ethanol fuels, almost doubling in some cases. The catalytic converter decreased acetaldehyde emissions to a great extent in the case of E10, whilst low catalytic efficiency on acetaldehyde was observed for E3. Generally, benzene and toluene emissions reduced following the addition ethanol to petrol, although this effect of was eliminated after the operation of the catalyst. Ethanol was identified in exhaust gases only when it was present in the fuel.

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[18] http://www.ukpia.com/industry_issues/fuels/biofuels_alternative_fuels.aspx

CONCAWE, EUCAR and the Joint Research Centre of the European Commission carried out a major test programme to investigate the influence of petrol vapour pressure and ethanol content on evaporative emissions from modern passenger cars (Martini *et al*., 2007). The results for evaporative emissions were summarised for this DfT project by Latham and Boulter (2009). Exhaust emissions of regulated and unregulated pollutants were also measured. Seven petrol passenger cars - representative of Euro 3 and Euro 4 technologies - were tested using 10 different test fuels. The test fuel matrix comprised 60 kPa and 70 kPa fuels with 5% and 10% ethanol 'splash'[19] blends, and 5% and 10% ethanol 'matched volatility'[20] blends. The exhaust emission measurements were performed over the NEDC. However, as the programme was designed to investigate evaporative emissions no vehicle conditioning procedure to minimise carry-over effects on exhaust emissions was included. Moreover, the long duration of the evaporative emissions test limited the opportunity for repeat exhaust emission tests. As a consequence, the measurements of exhaust emissions showed few statistically significant differences between fuels. The data were very variable and few firm conclusions could be drawn. Volumetric fuel consumption (litres/100 km) increased with increasing ethanol content, roughly in proportion to the oxygen content of the fuel, as would be expected. For the vehicles tested, a 10% ethanol blend increased fuel consumption by 3.97%. Another aspect that was analysed was the energy consumption of the vehicles when running on different fuels. It has been claimed that oxygen-containing fuels result in a better engine efficiency, and therefore less energy should be consumed to complete a test cycle. Statistical analyses revealed hardly any significant fuel effects on energy consumption.

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[19] Conventional petrol blended directly with ethanol, which increases fuel volatility.

[20] Specially tailored petrol blended with ethanol to account for increased fuel volatility.

6 Modelling fuel effects

6.1 NAEI approach (2006 inventory)

In the NAEI, scaling factors are applied to the basic emission factors for each year of the inventory. These scaling factors are designed to reflect the penetration of improved fuels and other technologies which ought to influence the baseline emission levels in future years. The NAEI takes account of the early introduction of certain emission and fuel quality standards, and additional voluntary measures to reduce emissions from road vehicles in the UK fleet. In addition the use of engine developments and exhaust abatement technologies, while designed to limit the emissions of specific pollutants such as PM, can have significant impacts on other non-regulated pollutants.

6.1.1 Introduction of ultra-low sulphur petrol and diesel

In January 2000, European Council Directive 98/70/EC relating to the quality of petrol and diesel fuels came into effect. This introduced tighter standards on a number of fuel properties affecting emissions. The principle changes in UK market fuels were the sulphur content and density of diesel, and the sulphur and benzene content of petrol. The volatility of summer blends of petrol was also reduced, affecting evaporative losses. During 2000-2004, virtually all the diesel sold in the UK was of ultra-low sulphur grade (<50 ppm sulphur), even though this low level of sulphur content was not required by the Directive until 2005. Similarly, ultra-low sulphur petrol (ULSP) became on-line in filling stations in 2000, with around one-third of sales being of ULSP quality during 2000, the remainder being of the quality specified by the Directive. In 2001-2004, virtually all unleaded petrol sold was of ULSP grade. The introduction of ultra-low sulphur petrol and diesel into the UK national fleet is taken into account in the 2006 NAEI.

Many bus fleets had converted to ultra-low sulphur diesel (ULSD) as early as 1997. It is assumed that prior to 2000, only buses had made a significant switch to ULSD, as this fuel was not widely available in UK filling stations. Based on government estimates, around 4,000 HGVs and buses were retrofitted with particulate traps in 2000, rising to 14,000 vehicles by the end of 2005 (Choudrie *et al*., 2008).

In the 2006 NAEI, emissions from HGVs and buses are scaled down according to the proportion of vehicles running on ultra-low sulphur diesel fuel in each year, the proportion fitted with oxidation catalysts or particulate traps (CRTs), and the effectiveness of these measures in reducing vehicle emissions. HGVs equipped with CRTs have their emissions reduced – relative to Euro II vehicles - by the amounts shown in Table 1. These vehicles will also be running on ULS diesel. The reductions in emissions from buses are shown in Table 2. It is assumed that a bus fitted with an oxidation catalyst or CRT is also running on ULS diesel. These scaling factors are relative to emissions from vehicles running on diesel with 500 ppm sulphur.

The impacts which ultra-low sulphur fuels would have on emissions from existing vehicles in the fleet was based on empirical formulae from EPEFE on the relationship between emissions and fuel properties, combined with information drawn from MEET (European Commission, 1999), the World-Wide Fuel Charter reports and various reports prepared by Millbrook and LT Buses on the effects of fuel properties on emissions from heavy-duty vehicles, and data on the effectiveness of oxidation catalysts on bus emissions (Murrells, 2000).

Table 1: Scaling factors for emissions from a Euro II HGV running on ultra-low sulphur diesel and fitted with an oxidation catalyst or CRT (Choudrie *et al*., 2008)

		CO	NMVOCs	NO_x
ULSD only	Urban	0.96	0.97	0.94
	Rural	1.01	1.02	0.99
ULSD + CRT	Urban	0.10	0.12	0.81
	Rural	0.10	0.12	0.85

Table 2: Scaling factors for emissions from a Euro II bus running on ultra-low sulphur diesel and fitted with an oxidation catalyst or CRT (Choudrie *et al*., 2008)

		CO	NMVOCs	NO_x
ULSD only	Urban	0.91	0.72	1.01
	Rural	1.01	1.02	0.99
ULSD + oxidation catalyst	Urban	0.20	0.39	0.97
	Rural	0.22	0.55	0.95
ULSD + CRT	Urban	0.17	0.19	0.90
	Rural	0.19	0.27	0.88

6.1.2 The effect of benzene content of petrol on exhaust emissions of benzene

The effect of the benzene content of petrol on exhaust emissions of benzene was included in the 2002 revision to the UK emission factors. According to the UK Petroleum Industries' Association (UKPIA), a significant decrease (76 %) in the benzene content of UK petrol occurred in 2000 in order to meet the lower EU limit of 1% introduced that year. Equations from EPEFE and MEET were used to derive factors reflecting the effect of reduced benzene content on benzene emissions from catalyst cars. No such information was available for non-catalyst cars. However, on the basis of fundamental combustion chemistry modelling and the significant reductions in ambient benzene concentrations observed in early 2000 at a number of air pollution monitoring sites, it was concluded that the reductions in the benzene content of petrol led to a proportional reduction in benzene emissions from non-catalyst cars. This is represented with an emission reduction scaling factor for this class of vehicle. For all vehicle categories except buses, benzene emissions were assumed to stabilise at 2001 levels. For buses, emissions were assumed to stabilise at 2006 levels.

6.2 COPERT III

In the COPERT III model (Ntziachristos and Samaras, 2000) the effects of different variables - vehicle mileage, enhanced inspection and maintenance, improved fuels, road gradient and vehicle load - on emissions are taken into account via the application of correction factors to the baseline emission functions. For fuels, the correction factors in COPERT III relate to the improved fuel specification in Directive 98/70/EC which became mandatory in Europe in January 2000 ('Fuel 2000') and January 2005 ('Fuel 2005') (see Chapter 2). The specifications of these fuels are displayed in Table 3 (petrol) and Table 4 (diesel).

Table 3: Petrol fuel specifications (Ntziachristos and Samaras, 2000).

Property	1996 baseline fuel (market average)	Fuel 2000	Fuel 2005
Sulphur (ppm)	165	130	40
RVP (kPa)	68 (summer), 81 (winter)	60 (summer), 70 (winter)	60 (summer), 70 (winter)
Aromatics (%vol)	39	37	33
Benzene (%vol)	2.1	0.8	0.8
Oxygen (%wt)	0.4	1.0	1.5
Olefins (%vol)	10	10	10
E100 (%)	52	52	52
E150 (%)	86	86	86
Trace lead (g/l)	0.005	0.003	0.003

Table 4: Diesel fuel specifications (Ntziachristos and Samaras, 2000).

Property	1996 baseline fuel (market average)	Fuel 2000	Fuel 2005
Cetane number (-)	51	53	53
Density at 15°C (kg m^{-3})	840	840	835
T_{95} (°C)	350	330	320
PAH (%)	9	7	5
Sulphur (ppm)	400	300	40
Aromatics (%vol)	28	26	24

Because of their improved properties, the fuels result in lower emissions from vehicles. Therefore, the stringent emission standards of Euro 3/III technology (introduced ~2000) are achieved with fuel quality ‘Fuel 2000’ and the more stringent emission standards of Euro 4/IV and 5/V with fuel quality ‘Fuel 2005’. Table 5 shows the baseline fuel which is used for each vehicle class.

Table 5: Baseline fuel for each vehicle class (Ntziachristos and Samaras, 2000).

Vehicle class	Baseline fuel	Available improved fuel
Pre-Euro3/ III	1996 baseline	Fuel 2000, Fuel 20005
Euro 3/III	Fuel 2000	Fuel 2005
Euro 4/IV	Fuel 2005	

However, the use of such fuels also results in reduced emissions from pre-Euro 3/III vehicle technologies, for which the 1996 market average fuel is considered as the baseline. The relative reductions are applied to both hot and cold start emissions. To correct the baseline emission factors, equations derived in the EPEFE programme are used (ACEA and EUROPIA, 1996).

The hot emission factors are corrected according to the equation:

$$\boldsymbol{FCe_{HOT;\,i,\,j,\,k} = (FCorr_{i,\,j,\,Fuel} / FCorr_{i,\,j,\,Base}) \times eHOT_{;\,i,\,j,\,k}} \quad \text{(Equation 1)}$$

Where:

$\boldsymbol{FCe_{HOT;\,i,\,j,\,k}}$ = The hot emission factor corrected for the use of improved fuel for pollutant ***i*** of vehicle class ***j*** driven on road types k

$\boldsymbol{FCorr_{i,\,j,\,Fuel}}$ = The fuel correction for pollutant ***i***, vehicle category ***j***, for the available improved fuel.

$\boldsymbol{FCorr_{i,\,j,\,Base}}$ = The fuel correction for pollutant ***i***, vehicle category ***j***, for the baseline fuel.

Table 6 displays the equations for different vehicle categories and pollutants.

Equation 1 should not be used to determine the deterioration of emissions where an older fuel is used in a newer technology (*e.g.* use of Fuel 2000 in Euro 4/IV vehicles).

Table 6: Correction factors for fuel properties (Ntziachristos and Samaras, 2000).

Vehicle category	Pollutant	Correction factor equation
Petrol cars and light goods vehicles	CO	$FCorr = [2.459 - 0.05513 \cdot (E100) + 0.0005343 \cdot (E100)^2 + 0.009226 \cdot (ARO) - 0.0003101 \cdot (97 - S)] \cdot [1 - 0.037 \cdot (O_2 - 1.75)] \cdot [1 - 0.008 \cdot (E150 - 90.2)]$
	VOC	$FCorr = [0.1347 + 0.0005489 \cdot (ARO) + 25.7 \cdot (ARO) \cdot e^{(-0.2642\,(E100))} - 0.0000406 \cdot (97 - S)] \cdot [1 - 0.004 \cdot (OLEFIN - 4.97)] \cdot [1 - 0.022 \cdot (O_2 - 1.75)] \cdot [1 - 0.01 \cdot (E150 - 90.2)]$
	NO_x	$FCorr = [0.1884 - 0.001438 \cdot (ARO) + 0.00001959 \cdot (ARO) \cdot (E100) - 0.00005302 \cdot (97 - S)] \cdot [1 + 0.004 \cdot (OLEFIN - 4.97)] \cdot [1 + 0.001 \cdot (O_2 - 1.75)] \cdot [1 + 0.008 \cdot (E150 - 90.2)]$
Diesel cars and light goods vehicles	CO	$FCorr = -1.3250726 + 0.003037 \cdot DEN - 0.0025643 \cdot PAH - 0.015856 \cdot CN + 0.0001706 \cdot T_{95}$
	VOC	$FCorr = -0.293192 + 0.0006759 \cdot DEN - 0.0007306 \cdot PAH - 0.0032733 \cdot CN - 0.000038 \cdot T_{95}$
	NO_x	$FCorr = 1.0039726 - 0.0003113 \cdot DEN + 0.0027263 \cdot PAH - 0.0000883 \cdot CN - 0.0005805 \cdot T_{95}$
	PM	$FCorr = (-0.3879873 + 0.0004677 \cdot DEN + 0.0004488 \cdot PAH + 0.0004098 \cdot CN + 0.0000788 \cdot T_{95}) \cdot [1 - 0.015 \cdot (450 - S)/100]$
Diesel heavy-duty vehicles	CO	$FCorr = 2.24407 - 0.0011 \cdot DEN + 0.00007 \cdot PAH - 0.00768 \cdot CN - 0.00087 \cdot T_{95}$
	VOC	$FCorr = 1.61466 - 0.00123 \cdot DEN + 0.00133 \cdot PAH - 0.00181 \cdot CN - 0.00068 \cdot T_{95}$
	NO_x	$FCorr = -1.75444 + 0.00906 \cdot DEN - 0.0163 \cdot PAH + 0.00493 \cdot CN + 0.00266 \cdot T_{95}$
	PM	$FCorr = [0.06959 + 0.00006 \cdot DEN + 0.00065 \cdot PAH - 0.00001 \cdot CN] \cdot [1 - 0.0086 \cdot (450 - S)/100]$

O_2 = Oxygenates in %
S = Sulphur content in ppm
ARO = Aromatics content in %
OLEFIN = Olefins content in %
E100 = Mid range volatility in %
E150 = Tail end volatility in %
DEN = Density at 15°C (kg m^{-3})
PAH = Polycyclic aromatics content in %
CN = Cetane number
T95 = Back end distillation in ^{o}C

6.3 COPERT 4

In December 2008 a draft revision to the Chapter on road vehicle emissions in the EMEP/CORINAIR Emission Inventory Guidebook was produced. The methodology presented in the Guidebook also forms the basis of COPERT 4. At the time of writing, the documentation suggests that the fuel corrections will be retained from COPERT III, but additional information is provided on the effects of biodiesel[21].

A literature review by Ntziachristos *et al.* (2007) led to the following conclusions regarding the effect of biodiesel on emissions from diesel-engined vehicles:

- The effect of biodiesel on CO_2 emissions, when expressed as 'tank-to-wheel', is limited.
- The presence of oxygen atoms in biodiesel molecules leads to an increase in NO_x and a decrease in PM, HC and CO emissions for all diesel engine types.
- The magnitude of the biodiesel effect depends on the engine and emission control technology of the vehicle (oxidation catalyst, de-NO_x, particulate filter).
- The effect on emissions increases monotonically with the biodiesel blend ratio in the fossil fuel.

Linear regression functions were developed on the basis of the available experimental data. Based on these functions, Table 7 shows the expected effect per vehicle technology for the three most widespread biodiesel blends (B10, B20, B100). Blending of petroleum diesel with biodiesel in a proportion less than 10% is expected to have no effect on emissions. Pure biodiesel (B100) was not considered to be relevant for general use in light-duty vehicles, but only in specific applications of captive fleets, such as urban buses.

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[21] http://transportpanel.jrc.ec.europa.eu/draft.html

Table 7: Correction factors proposed for different biodiesel blends, according to vehicle type (Ntziachristos *et al*., 2007).

Pollutant	Vehicle type	B10	B20	B100
CO_2	PC	-1.5%	-2.0%	
	LD	-0.7%	-1.5%	
	HD	0.2%	0.0%	0.1%
NO_x	PC	0.4%	1.0%	
	LD	1.7%	2.0%	
	HD	3.0%	3.5%	9.0%
PM	PC	-13.0%	-20.0%	
	LD	-15.0%	-20.0%	
	HD	-10.0%	-15.0%	-47.0%
CO	PC	0.0%	-5.0%	
	LD	0.0%	-6.0%	
	HD	-5.0%	-9.0%	-20.0%
HC	PC	0.0%	-10.0%	
	LD	-10.0%	-15.0%	
	HD	-10.0%	-15.0%	-17.0%

PC = passenger car , LD = light-duty (goods) vehicle, HD = heavy-duty vehicle

The values proposed in Table 7 correspond to Euro 3/III vehicle/engine technology. The effect of biodiesel on other technologies may vary, but the extent of the variation is difficult to estimate in the absence of detailed literature data. For NO_x, CO_2 and CO, any effect of technology should be negligible, given the marginal effect of biodiesel on these pollutants in general. The effect of biodiesel on PM for different technologies is more difficult to assess. For older diesel technologies with no advanced combustion concepts and after-treatment systems, biodiesel may lead to higher reductions than those shown. For more recent technologies, with ultra-high-pressure combustion and after-treatment, the biodiesel effect is difficult to predict. Hence, the proposed values should be used with care for post-Euro 3/III diesel technologies (Ntziachristos *et al*., 2007).

For NO_x and PM the proposed values concur with the USEPA findings (Figure 9). For CO and HC the reductions in emissions are lower than those observed by the USEPA.

6.4 ARTEMIS

6.4.1 Cars and light goods vehicles

No correction factors for fuel properties in relation to cars and light goods vehicles were derived from the experimental work in ARTEMIS.

6.4.2 Heavy-duty vehicles

For HDVs a modelling approach was developed in ARTEMIS for assessing the effects of fuel parameters on emissions of CO, HC, NO_x and PM. The approach again involves the definition of a baseline fuel, for which there are known basic emission factors, and the application of a percentage change in emissions based upon the differences between the test fuel and the baseline fuel. The percentage changes in emissions are calculated from a series of regression models which take into account fuel properties such as sulphur content, density, specific gravity, polyaromatic content and cetin number. The effects are based upon a review of various measurement programmes, such as EPEFE and the USEPA Heavy-Duty Engine Working Group Programme (Rexeis *et al*., 2005 and references therein). The baseline fuel properties for pre-Euro I, Euro I and Euro II engines were taken from the Worldwide Diesel Fuel Quality Surveys. Baseline fuel properties for Euro III engines were defined based on the average quality of the corresponding fuels used in the ARTEMIS tests, Baseline fuel properties for Euro IV and Euro V generations were estimated based on the requirements of vehicle and engine manufacturers, as published in the latest World–Wide Fuel Charter. The proposed baseline fuel properties are summarised in Table 8.

Table 8: Baseline fuel properties (Rexeis *et al*., 2005).

Emission legislation	Density (kg m^{-3})	Cetane number	Cetane difference	Poly-aromatics (%)	Total aromatics (%)	T10 (^{o}C)	T50 (^{o}C)	T95 (^{o}C)	Sulphur Content (ppm)	Oxygen content (%m)
Pre-Euro I	835	51	0	6	25	205	260	345	1500	0
Euro I	835	51	0	6	25	205	260	340	1300	0
Euro II	830	53	0	5	20	205	260	340	300	0
Euro III	830	53	0	4	20	210	265	340	40	0
Euro IV	830	55	0	2	15	210	265	340	10	0
Euro V	830	55	0	2	15	210	265	340	5	0

The percentage changes in emissions were calculated using the models described below. This percentage could then be applied as a change to the emission factors estimated by the main model, based on the baseline fuels. Rexeis *et al*. (2005) recommended the use of the functions shown in Table 9.

Table 9: Regression equations.

Pollutant	Function	Units	Source
CO	$2.24407 - 0.00111\boldsymbol{D} + 0.00007\boldsymbol{P} - 0.00768\boldsymbol{C} - 0.00087\boldsymbol{T95}$	g kWh^{-1}	EPEFE
HC	$\exp(5.32059 - 0.1875\boldsymbol{CN} + 0.001571\boldsymbol{CN}^2 - 0.0009809\boldsymbol{T10} - 0.002448\boldsymbol{T50} - 0.1880\boldsymbol{CD} + 0.003507\boldsymbol{CN} * \boldsymbol{CD})$	g hph^{-1}	USEPA
NO_x	$\exp(0.50628 - 0.002779\boldsymbol{CD} + 0.002922\boldsymbol{A} + 1.3966\boldsymbol{G} - 0.0004023\boldsymbol{T50})$	g hph^{-1}	USEPA
PM	$(0.06959 + 0.00006\boldsymbol{D} + 0.00065\boldsymbol{P} - 0.00001\boldsymbol{C}) * [1 - 0.000086 (450 - \boldsymbol{S})]$	g kWh^{-1}	EPEFE

D – density. Kg m^{-3}; ***G*** – specific gravity; ***P*** – poly-aromatics content. % m; ***A*** – total aromatics content. % vol; ***C*** – cetane number; ***CN*** – natural cetane number; ***CD*** – cetane difference due to additizing; ***S*** – sulphur content. ppm; ***T10*** – T10 temperature. ^{o}F; ***T50*** – T50 temperature. ^{o}F; ***T95*** – T95 temperature. ^{o}C.

6.4.3 Two-wheel vehicles

For two-wheel vehicles the ARTEMIS model can be used to estimate emissions for trade fuel and fuel meeting the future WWFC4 requirements. Similar factors are applied to two- and four-stroke engines, and CO, HC, ultimate CO_2 and fuel consumption. For NO_x a distinction is made with regard to engine type. The factors to be applied to address the effects of fuel properties are given in Table 10.

Table 10: Factors to be applied on standard emission factors to address the effects of fuel.

Fuel	Engine type	CO (%)	HC (%)	NO_x (%)	FC and ultimate CO_2 (%)
Trade fuel	2-stroke	100%	100%	100%	100%
	4-stroke	100%	100%	100%	100%
WWFC4 fuel	2-stroke	85%	95%	85%	100%
	4-stroke	85%	95%	110%	100%

7 Fuel scaling factors applicable to 2009 emission factors

7.1 The 2009 emission factors

The derivation of 'basic' emission factors for UK road vehicles was described in Task Report 3 (Boulter and Barlow, 2009). The term 'basic' is used here to indicate that the emission factors are either normalised for mileage or reflect current vehicle and fuel technologies, and should be used in conjunction with scaling factors when estimating actual emissions. Scaling factors to account for the following effects in different years were therefore investigated:

- Mileage effects relating to vehicle samples.
- Fuel composition effects.
- Increased market penetration of biofuels for use in existing petrol and diesel-engined vehicles.
- Effects of future technologies.

The development of mileage and technology scaling factors is described by Boulter (2009). The development of the fuel scaling factors is described below.

7.2 Fuel composition scaling factors

If fuel composition scaling factors are to be applied to the basic emission factors, these scaling factors ought to relate in some way to the fuels which were used for testing, and appropriate baseline fuels would need to be specified. In other words, any adjustment factors which are used must be relevant to the measurements to which they are being applied. However, detailed fuel specifications were only available for a small proportion of the emission tests included in the emission factor databases, and therefore no precise baseline fuel specifications could be established. In order to determine fuel composition scaling factors it could only be assumed that each vehicle was tested on the fuel which was commercially available at the time of the test. This was complicated by the fact that many of the vehicles in the databases were not tested in the UK, and the fuels used in different European countries would have had different composition and properties. Furthermore, for many vehicles in the databases the test date was not known. The scaling factor approach for fuel composition therefore had to be rather simple.

In order to the derive fuel composition scaling factors an adapted version of the method presented in COPERT III (and retained in COPERT 4) was used. For CO, HC, NO_x and PM the fuel composition scaling factor for each reference year was taken to be the value of $\boldsymbol{FCorr_{i,\,j,\,Fuel}}$ / $\boldsymbol{FCorr_{i,\,j,\,Base}}$ in Equation 1. The baseline fuels are specified in Table 11 and Table 12. These are identical to those used in COPERT, except for the addition of a 'Fuel 2009' with a maximum sulphur content of 10 ppm.

The correspondence between fuels and emission standards for all vehicle types is given in Table 13. Again, this is taken from COPERT, with the addition of a 2009 fuel. It is assumed that there are no further improvements in fuels beyond 2009. The correspondence between fuel and emission standards was applied to all light-duty and heavy-duty vehicles. No fuel composition scaling factors were determined for two-wheel vehicles. The resulting fuel composition scaling factors are given in Table 14 to Table 17.

Table 11: Petrol fuel specifications.

Property	1996 baseline fuel (market average)	Fuel 2000	Fuel 2005	Fuel 2009
Sulphur (ppm)	165	130	40	10
Aromatics (%vol)	39	37	33	As 2005
Benzene (%vol)	2.1	0.8	0.8	As 2005
Oxygen (%wt)	0.4	1.0	1.5	As 2005
Olefins (%vol)	10	10	10	As 2005
E100 (%)	52	52	52	As 2005
E150 (%)	86	86	86	As 2005

Table 12: Diesel fuel specifications.

Property	1996 baseline fuel (market average)	Fuel 2000	Fuel 2005	Fuel 2009
Cetane number (-)	51	53	53	As 2005
Density at 15^{o}C (kg m^{-3})	840	840	835	As 2005
T_{95} (^{o}C)	350	330	320	As 2005
PAH (%)	9	7	5	As 2005
Sulphur (ppm)	400	300	40	10
Aromatics (%vol)	28	26	24	As 2005

Table 13: Correspondence between fuels and emission standards (LDVs and HDVs).

Fuel	Emission standard	Baseline fuel	Available improved fuels
Petrol	Pre-Euro 1/I	1996	2000, 2005
	Euro 1/I	1996	2000, 2005
	Euro 2/II	1996	2000, 2005
	Euro 3/III	2000	2005
	Euro 4/IV	2005	2009
	Euro 5/V	2009	-
	Euro 6/VI	2009	-
Diesel	Pre-Euro 1/I	1996	2000, 2005
	Euro 1/I	1996	2000, 2005
	Euro 2/II	1996	2000, 2005
	Euro 3/III	2000	2005
	Euro 4/IV	2005	2009
	Euro 5/V	2009	-
	Euro 6/VI	2009	-

Table 14: Fuel composition scaling factors for CO.

Vehicle type	Fuel type	Emission standard	Baseline fuel	Scaling factor by year																																			
				1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Car, taxi, LGV	Petrol	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.959	0.959	0.959	0.959	0.959	0.897	0.897	0.897	0.897	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.959	0.959	0.959	0.959	0.959	0.897	0.897	0.897	0.897	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	0.959	0.959	0.959	0.959	0.959	0.897	0.897	0.897	0.897	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891	0.891
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.936	0.936	0.936	0.936	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930	0.930
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Diesel	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.933	0.933	0.933	0.933	0.933	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.933	0.933	0.933	0.933	0.933	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	0.933	0.933	0.933	0.933	0.933	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907	0.907
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
HDV	Diesel	Pre-Euro I	1996	1.000	1.000	1.000	1.000	1.000	1.003	1.003	1.003	1.003	1.003	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026
		Euro I	1996	1.000	1.000	1.000	1.000	1.000	1.003	1.003	1.003	1.003	1.003	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026
		Euro II	1996	1.000	1.000	1.000	1.000	1.000	1.003	1.003	1.003	1.003	1.003	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026	1.026
		Euro III	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022	1.022
		Euro IV	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro V	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro VI	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 15: Fuel composition scaling factors for HC.

Vehicle type	Fuel type	Emission standard	Baseline fuel	Scaling factor by year																																			
				1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Car, taxi, LGV	Petrol	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.971	0.971	0.971	0.971	0.971	0.924	0.924	0.924	0.924	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.971	0.971	0.971	0.971	0.971	0.924	0.924	0.924	0.924	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	0.971	0.971	0.971	0.971	0.971	0.924	0.924	0.924	0.924	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.952	0.952	0.952	0.952	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Diesel	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.951	0.951	0.951	0.951	0.951	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.951	0.951	0.951	0.951	0.951	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	0.951	0.951	0.951	0.951	0.951	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933	0.933
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
HDV	Diesel	Pre-Euro I	1996	1.000	1.000	1.000	1.000	1.000	1.028	1.028	1.028	1.028	1.028	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067
		Euro I	1996	1.000	1.000	1.000	1.000	1.000	1.028	1.028	1.028	1.028	1.028	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067
		Euro II	1996	1.000	1.000	1.000	1.000	1.000	1.028	1.028	1.028	1.028	1.028	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067	1.067
		Euro III	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038	1.038
		Euro IV	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro V	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro VI	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 16: Fuel composition scaling factors for NO_x.

Vehicle type	Fuel type	Emission standard	Baseline fuel	Scaling factor by year																																			
				1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Car, taxi, LGV	Petrol	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	0.995	0.995	0.978	0.978	0.978	0.978	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	0.995	0.995	0.978	0.978	0.978	0.978	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	0.995	0.995	0.978	0.978	0.978	0.978	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969	0.969
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.983	0.983	0.983	0.983	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Diesel	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	1.011	1.011	1.011	1.011	1.011	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	1.011	1.011	1.011	1.011	1.011	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	1.011	1.011	1.011	1.011	1.011	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014	1.014
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003	1.003
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
HDV	Diesel	Pre-Euro I	1996	1.000	1.000	1.000	1.000	1.000	0.998	0.998	0.998	0.998	0.998	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993
		Euro I	1996	1.000	1.000	1.000	1.000	1.000	0.998	0.998	0.998	0.998	0.998	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993
		Euro II	1996	1.000	1.000	1.000	1.000	1.000	0.998	0.998	0.998	0.998	0.998	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993	0.993
		Euro III	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994
		Euro IV	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro V	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro VI	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 17: Fuel composition scaling factors for PM.

Vehicle type	Fuel type	Emission standard	Baseline fuel	Scaling factor by year																																			
				1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Car, taxi, LGV	Diesel	Pre-Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.957	0.957	0.957	0.957	0.957	0.852	0.852	0.852	0.852	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848
		Euro 1	1996	1.000	1.000	1.000	1.000	1.000	0.957	0.957	0.957	0.957	0.957	0.852	0.852	0.852	0.852	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848
		Euro 2	1996	1.000	1.000	1.000	1.000	1.000	0.957	0.957	0.957	0.957	0.957	0.852	0.852	0.852	0.852	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848	0.848
		Euro 3	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.891	0.891	0.891	0.891	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887	0.887
		Euro 4	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995
		Euro 5	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro 6	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
HDV	Diesel	Pre-Euro I	1996	1.000	1.000	1.000	1.000	1.000	0.981	0.981	0.981	0.981	0.981	0.946	0.946	0.946	0.946	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944
		Euro I	1996	1.000	1.000	1.000	1.000	1.000	0.981	0.981	0.981	0.981	0.981	0.946	0.946	0.946	0.946	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944
		Euro II	1996	1.000	1.000	1.000	1.000	1.000	0.981	0.981	0.981	0.981	0.981	0.946	0.946	0.946	0.946	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944	0.944
		Euro III	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.965	0.965	0.965	0.965	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962
		Euro IV	2005	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997
		Euro V	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Euro VI	2009	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

7.3 Biofuel scaling factors

Any scaling factors which allow for the introduction of biofuels need to take into account the likely timescale for the introduction and the effects per vehicle (it is assumed that all vehicles are affected). The use of particular fuel blends must also be considered. In the case of CO_2 emissions, allocation should also be addressed. According to the COPERT 4 methodology, to be consistent with the IPCC 1996 and IPCC 2006 guidelines, only the fossil fuel contribution should be taken into account in the calculation of emissions from road transport, and emissions associated with the use of biofuels should be attributed to the 'Land Use, Land-Use Change and Forestry' sector.

7.3.1 Timescale for introduction

The RTFO, which came into effect in April 2008, now requires 5% of all UK fuel sold on UK forecourts to come from a renewable source by 2013/14. In the Government's Transport Analysis Guidance (Web-TAG)[22], it is estimated that the introduction of biofuels over the next 4 years (which involves blending biofuels with conventional fuel) will result in a reduction in the grammes of carbon released per litre of fuel burnt (although at the time of writing the values do not appear to have been updated to reflect the latest RTFO requirements.

The European Environment Agency[23] recently assessed the amount of biomass that could technically be available for energy production in each Member State without increasing pressures on the environment. For the UK, the report's conclusions indicated that the UK could produce enough biofuels for around 2.5% of the road transport fuel needs in the short term. However, as biofuels are a globally traded commodity the proportion of domestically sourced agricultural crops used to meet UK biofuel targets will be determined by the market rather than theoretical production capacity (DEFRA, 2007).

According to Choudrie *et al*. (2008) there are, as yet, no definitive, official national statistics on the amount of biofuel used for road transport in the UK. Biodiesel blended with conventional diesel is starting to become more widely available in the UK and approximately 499 sites were selling biodiesel blend at the end of 2006 – mostly derived from reprocessed vegetable oil. In 2006/7 UK biodiesel consumption was 220 million litres, representing 0.9% of UK sales of conventional diesel. The additional duty incentive of 20 pence per litre on bio-ethanol that came into effect at the start of 2005 gave a modest boost to demand for blending into petrol[24].

Bioethanol is mixed with petrol in the UK, and is sold at a number of filling stations. However, although production of bioethanol in the UK is increasing, the bioethanol fuel industry is still not well developed, and there is no specific timescale for more extensive introduction of the fuels at retail outlets.

7.3.2 Effects per vehicle

Biodiesel

The British standard for diesel (BS EN 590) permits a biofuel content of up to 5% by volume without affecting the vehicle manufacturer's warranty. For diesel this limit is being raised to 7% in 2009. Oil companies and vehicle manufacturers have also agreed a standard (BS EN 14214) for vegetable oils suitable for blending with conventional diesel to ensure that the product meets the technical requirements of modern diesel engines[25].

A methodological approach for calculating the effects per vehicle of biodiesel blends - based upon a recent review of the literature - is provided in COPERT 4 method (see Section 6.3). However, the blending of petroleum diesel with biodiesel in a proportion of less than 10% is expected to have no effect on exhaust emissions.

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[22] http://www.webtag.org.uk/webdocuments/3_Expert/3_Environment_Objective/3.3.5.htm

[23] http://reports.eea.europa.eu/eea_report_2006_7en

[24] http://www.ukpia.com/industry_issues/fuels/alternative_fuels/faqs_biofuels.aspx

[25] http://www.ukpia.com/industry_issues/fuels/alternative_fuels.aspx?referrertabid=2107&linktext=Alternative+Fuels

Bioethanol-petrol blends

As stated earlier, most modern petrol cars will run on a 10% mixture of ethanol to petrol, although warranties may state that a mix of 5% is the maximum allowed. A number of studies have been conducted to quantify the effects of ethanol fuels on vehicle emissions, with much of the available data being based on fuels containing up to 10% by volume of ethanol. These studies have generally shown that ethanol/petrol blends reduce CO, HC and PM emissions, but also that vehicles with newer technologies show smaller reductions compared to vehicles with older technologies. The effect of blends on NO_x emissions are mixed, and exhaust CO_2 emissions appear not to be greatly affected.

7.3.3 Conclusions

From the evidence, it appears that emission scaling factors for biodiesel are not required in the UK, given that the blending of petroleum diesel with biodiesel in a proportion of less than 10% is expected to have no effect on emissions, and the biofuel content of diesel is not predicted to exceed 5% by volume

A similar argument appears to be justifiable for bioethanol blends, although there appear to be few recommendations for specific adjustment factors. Consequently, no scaling factors are provided here.

8 Summary and recommendations

TRL has derived 'basic' emission factors for UK road vehicles (Boulter and Barlow, 2009). The term 'basic' is used here to indicate that the emission factors are either normalised for mileage or reflect current vehicle and fuel technologies. This Report reviewed the effects of fuel properties on emissions and resulted in the development of appropriate scaling factors for different years.

8.1 Fuel composition effects

In this work, two aspects of fuel sulphur content were reviewed. These aspects were the effects of switching from ULS fuels (50 ppm sulphur) to sulphur-free fuels (10 ppm sulphur), and potential 'catalyst recovery' associated with a reduction in fuel sulphur content.

Within a given Euro class the effects of fuel sulphur content on NO_x and PM emissions are generally either not significant or rather small. Reductions in fuel sulphur content from 50 ppm to 10 ppm seem unlikely to bring substantial emissions benefits for current Euro 3/III and 4/IV vehicle technologies. The main exception may be PM emissions.

Emissions from modern petrol Euro 3 and Euro 4 cars do not appear to show a change in sensitivity to fuel sulphur level with age. It is possible that older petrol vehicles could show some degree of catalyst recovery (*i.e*. lower emission levels) when used on sulphur-free fuel. However, such effects are rather difficult to quantify as there seems to be little interest in testing old vehicles on new fuels.

Lowering fuel aromatic content will generally result in reduced PAH emissions from older technology engines. Diesel vehicles with after-treatment devices are less sensitive to the fuel aromatic content. An increase in cetane number generally results in a decrease in emissions of CO, HC and NO_x. Again, for diesel vehicles equipped with oxidation catalysts or PM filters, emissions will generally tend to be less sensitive to cetane number. The effects on PM appear to be rather variable. Changes in other fuel properties, such as volatility and olefin content, can also result in small, sometimes significant, changes in emissions.

8.2 Effects of biofuels

The need to reduce greenhouse gas emissions has accelerated efforts to increase the use of non-fossil fuels in road transport, as reflected in the Biofuels Directive and the RTFO. The effects on exhaust emissions of two main types of biofuel were briefly reviewed: biodiesel blends and ethanol blends. These are the main biofuels available in the UK.

There is a general agreement in the literature that biodiesel and its blends decrease exhaust emissions of CO, HC and PM, whereas NO_x emissions with biodiesel appear to increase. From the evidence, it appears that the blending of petroleum diesel with biodiesel in a proportion of less than 10% is expected to have no effect on emissions, and in the near future the biofuel content of diesel is not predicted to exceed 5% by volume

The use of ethanol in diesel fuel can yield significant reductions in particulate matter (PM) emissions from motor vehicles. However, there are many technical barriers to the direct use of ethanol in diesel fuel. Studies have generally shown that ethanol/petrol blends reduce CO, HC and PM emissions, but also that vehicles with newer technologies show smaller reductions compared to vehicles with older technologies. The effect of blends on NO_x emissions are mixed, and exhaust CO_2 emissions appear not to be greatly affected. However, there appear to be few recommendations for specific adjustment factors.

8.3 Scaling factors

8.3.1 Fuel composition

In order to the derive fuel composition scaling factors an adapted version of the method presented in COPERT III/4 was used. For CO, HC, NO_x and PM the fuel composition scaling factor for each reference year was calculated, with the fuel properties in different years being identical to those used in COPERT, except for the addition of a ‘Fuel 2009’ having a maximum sulphur content of 10 ppm. Fuel composition scaling factors were calculated for all light-duty and heavy-duty vehicles. No fuel composition scaling factors were determined for two-wheel vehicles. The resulting scaling factors should be used in conjunction with the basic 2008 emission factors.

8.3.2 Biofuels

From the evidence, it appears that emission scaling factors for biodiesel are not required in the UK, given that the blending of petroleum diesel with biodiesel in a proportion of less than 10% is expected to have no effect on emissions, and the biofuel content of diesel is not predicted to exceed 5% by volume.

A similar argument appears to be justifiable for bioethanol blends, although there appear to be few recommendations for specific adjustment factors. Consequently, no scaling factors are provided here.

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Appendix A: Abbreviations and terms used in the Task Reports

ACEA	European Automobile Manufacturers Association.
ADMS	Atmospheric Dispersion Modelling System.
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems. An EC 5th Framework project, funded by DG TREN and coordinated by TRL. http://www.trl.co.uk/artemis/introduction.htm
AURN	Automatic Urban and Rural Network. Automatic monitoring sites for air quality that are or have been operated on behalf of the Department for Environment, Food and Rural Affairs in the UK.
AVERT	Adaptation of Vehicle Environmental Response by Telematics. Project funded by the Foresight Vehicle programme. http://www.foresightvehicle.org.uk/dispproj1.asp?wg_id=1003
BP	British Petroleum.
CEN	European Standards Organisation.
CERC	Cambridge Environmental Research Consultants, the developers of the ADMS model suite.
Cetane number (CN)	Cetane number is a measure of the combustion quality of diesel fuel. Cetane is an alkane molecule that ignites very easily under compression. All other hydrocarbons in diesel fuel are indexed to cetane (index = 100) as to how well they ignite under compression. Since there are hundreds of components in diesel fuel, the overall CN of the diesel is the average of all the components. There is very little actual cetane in diesel fuel. Generally, diesel engines run well with a CN between 40 and 55.
CITA	International Motor Vehicle Inspection Committee, based in Brussels.
CNG	Compressed natural gas (primarily methane).
CH_4	Methane.
CO	Carbon monoxide.
CO_2	Carbon dioxide.
uCO_2	‘Ultimate’ CO_2.
COLDSTART	A model for cold-start emissions developed by VTI in Sweden.
CONCAWE	The Oil Companies’ European Association for Environment, Health and Safety in Refining and Distribution.
COST	European Cooperation in Science and Technology.
CRT	Continuously Regenerating Trap – a trademark of Johnson Matthey.
CVS	Constant-volume sampler.
COPERT	COmputer Program to calculate Emissions from Road Transport. http://lat.eng.auth.gr/copert/
CORINAIR	CO-oRdinated INformation on the Environment in the European Community - AIR
DEFRA	Department for Environment, Food and Rural Affairs.

DfT	Department for Transport, UK.
DI	Direct injection.
DMRB	Design Manual for Roads and Bridges. http://www.standardsforhighways.co.uk/dmrb/
DPF	Diesel particulate filter.
DTI	Department of Trade and Industry (now the Department for Business, Enterprise and Regulatory Reform – BERR).
Driving cycle	The term 'driving cycle' (or sometimes 'duty cycle' is used to describe how a vehicle is to be operated during a laboratory emission test. A driving cycle is designed to reflect some aspect of real-world driving, and usually describes vehicle speed as a function of time.
Driving pattern	The term 'driving pattern' is used to describe how a vehicle is operated under real-world conditions, based on direct measurement, or the time history of vehicle operation specified by a model user. In the literature, this is also often referred to as a driving cycle. However, in this work it has been assumed that a driving pattern only becomes a driving cycle once it has been used to measure emissions.
Dynamics	Variables which emission modellers use to describe the extent of transient operation (see entry below for 'transient') in a driving cycle (*e.g.* maximum and minimum speed, average positive acceleration). Can be viewed as being similar to the concept of the 'aggressiveness' of driving.
DVPE	Dry vapour pressure equivalent. The difference between DVPR and (the older) RVP is the measurement method. DVPE is measured 'dry' after removing all moisture from the test chamber prior to injection of the sample. This overcomes the unpredictability of results experienced when testing samples containing oxygenates by the conventional RVP method. DVPE is measured at a temperature of 37.8°C.
EC	European Commission.
ECE	Economic Commission for Europe.
EGR	Exhaust gas recirculation.
EIA	Environmental Impact Assessment
EMEP	Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe.
EMFAC	EMission FACtors model, developed by the California Air Resources Board. EMFAC 2007 is the most recent version.
EMPA	One of the research institutes of the Swiss ETH organisation.
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ETC	European Transient Cycle.
EU	European Union.
EUDC	Extra Urban Driving Cycle.
EXEMPT	EXcess Emissions Planning Tool.
FAME	Fatty acid methyl ester.
FHB	Fachhochschule Biel (FHB): Biel University of applied science, Switzerland.
FID	Flame ionisation detector.
FIGE (or FiGE)	Forschungsinstitut Gerausche und Erschutterungen (FIGE Institute), Aachen, Germany. Now TUV Automotive GmbH.

Fischer-Tropsch diesel (FTD)	Fischer-Tropsch diesel is a premium diesel product with a very high cetane number (75) and zero sulphur content. It is generally produced from natural gas.
FTP	Federal Test Procedure – the driving cycle used in US emission tests.
FTIR	Fourier-transform infrared spectroscopy.
GC/MS	Gas chromatography/mass spectrometry.
GDI	Gasoline Direct Injection.
GHG	Greenhouse gas.
GVW	Gross vehicle weight.
HBEFA/Handbook	Handbook Emission Factors for Road Transport (Handbuch Emissionsfaktoren des Strassenverkehrs). An emission model used in Switzerland, Germany and Austria. http://www.hbefa.net/
HDV	Heavy-duty vehicles. Road vehicles greater than 3.5 tonnes (GVW), where GVW is the gross weight of the vehicle, *i.e.* the combined weight of the vehicle and goods.
HGV	Heavy goods vehicles. Goods vehicles greater than 3.5 tonnes GVW.
HOV	High-occupancy vehicle.
HyZem	HYbrid technology approaching efficient Zero Emission Mobility.
IDI	Indirect injection.
IM	Inspection and Maintenance: in-service vehicle road worthiness testing.
INFRAS	A private and independent consulting group based in Switzerland.
INRETS	Institut National de Recherche sur les Transports et leur Sécurité, France.
IUFC-15	INRETS urbain fluide court. Short, urban free-flow driving cycle.
IRC-15	INRETS route courte. Short rural driving cycle.
JCS	A European Joint Commission funded project: *The inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency*, carried out on behalf of EC DGs for Environment (DG XI) Transport (DG VII) and Energy (DG XVII). Project coordinated by LAT, University of Thessaloniki.
LDV	Light-duty vehicles. Road vehicles less than 3.5 tonnes GVW, including cars and light goods vehicles.
LGV	Goods/commercial vehicles less than 3.5 tonnes GVW.
LPG	Liquefied petroleum gas.
M25	London orbital motorway.
MEET	Methodologies for Estimating air pollutant Emissions from Transport. European Commission 4th Framework project coordinated by INRETS.
MHDT	Millbrook Heavy-Duty Truck (driving cycle).
MLTB	Millbrook London Transport Bus (driving cycle).
MOBILE	USEPA vehicle emission modelling software.
MODEM	Modelling of Emissions and Fuel Consumption in Urban Areas. A research project within the EU DRIVE programme coordinated by INRETS.
MOUDI	Micro-orifice uniform deposit impactor.
MPI	Multi-point injection.

MTC	AVL MTC Motortestcenter AB, Sweden.
MVEG	Motor Vehicle Emission Group.
NAEI	National Atmospheric Emissions Inventory (UK). http://www.naei.org.uk/
NEDC	New European Driving Cycle.
NETCEN	National Environmental Technology Centre.
N_2O	Nitrous oxide.
NH_3	Ammonia.
NMVOC	Non-methane volatile organic compounds.
NO	Nitric oxide.
NO_2	Nitrogen dioxide.
NO_x	Total oxides of nitrogen.
OBD	On-board diagnostics.
OSCAR	Optimised Expert System for Conducting Environmental Assessment of Urban Road Traffic. A European Fifth Framework research project, funded by DG Research. Project and coordinated by the University of Hertfordshire.
PAHs	Polycyclic aromatic hydrocarbons.
PARTICULATES	An EC Fifth Framework research project, funded by DG TREN and coordinated by LAT, Thessaloniki. http://lat.eng.auth.gr/particulates/
PHEM	Passenger car and Heavy-duty Emission Model. One of the emission models developed in COST Action 346 and the ARTEMIS project.
PM	Particulate matter.
PM_{10}	Airborne particulate matter with an aerodynamic diameter of less than 10 µm.
$PM_{2.5}$	Airborne particulate matter with an aerodynamic diameter of less than 2.5 µm.
PMP	Particle Measurement Programme.
POPs	Persistent organic pollutants.
ppm	Parts per million.
PSV	Public Service Vehicle.
Road characteristics	Information relating to the road, such as the geographical location (*e.g.* urban, rural), the functional type (*e.g.* distributor, local access), the speed limit, the number of lanes and the presence or otherwise of traffic management measures.
RME	Rapeseed methyl ester.
RTC	Reference test cycles.
RTD	Real-time diurnal (evaporative emissions).
RTFO	Renewable Transport Fuel Obligation.
RVP	Reid vapour pressure.
SCR	Selective catalytic reduction.
SEA	Strategic Environmental Assessment.
SHED	Sealed Housing for Evaporative Determination.

SMMT	Society of Motor Manufacturers and Traders.
SO_2	Sulphur dioxide.
TEE	Traffic Energy and Emissions (model).
THC/HC	Total hydrocarbons.
TNO	TNO Automotive, The Netherlands. The power train and emissions research institute of the holding company, TNO Companies BV.
Traffic characteristics/ conditions	Information relating to the bulk properties of the traffic stream – principally its speed, composition and volume/flow or density.
TRAMAQ	Traffic Management and Air Quality Research Programme. A research programme funded by the UK Department for Transport. http://www.dft.gov.uk/pgr/roads/network/research/tmairqualityresearch/trafficmanagementandairquali3927
Transient	Relates to when the operation of a vehicle is continuously varying, as opposed to being in a steady state.
TRL	TRL Limited (Transport Research Laboratory), UK.
TRRL	Transport and Road Research Laboratory - former name of TRL.
TUG	Technical University of Graz, Austria.
TUV	TÜV Rheinland, Germany. Exhaust emission testing used to be undertaken at this institute based in Cologne. These activities were transferred to another institute in the TUV group, based in Essen, in 1999.
TWC	Three-way catalyst.
UG214	A project within DfT's TRAMAQ programme which involved the development of realistic driving cycles for traffic management schemes.
UKEFD	United Kingdom Emission Factor Database (for road vehicles).
UKPIA	UK Petroleum Industries Association
ULSD	Ultra-low-sulphur diesel.
UROPOL	Urban ROad POLlution model.
USEPA	United States Environmental Protection Agency.
UTM/UTMC	Urban Traffic Management / Urban Traffic Management and Control.
Vehicle operation	The way in which a vehicle is operated (*e.g.* vehicle speed, throttle position, engine speed, gear selection).
VeTESS	Vehicle Transient Emissions Simulation Software.
VOCs	Volatile organic compounds.
VOSA	Vehicle and Operator Services Agency
WMTC	World Motorcycle Test Cycle. A common motorcycle emissions certification Procedure. The cycle is divided into urban, rural, and highway driving.
WSL	Warren Spring Laboratory.
WVU	West Virginia University, US.
WWFC	World-Wide Fuel Charter. The World Wide Fuel Charter is a joint effort by European, American and Japanese automobile manufacturers and other related associations, and recommends global standards for fuel quality, taking into account the status of emission technologies.

Appendix B: Cars used in CONCAWE tests

Table B1: Details of cars tested by CONCAWE (Doel *et al.*, 2005).

Phase	Vehicle code	Year	Fuel	Engine (litres)	Combustion system	Aspiration	Fuel injection control	EGR	Exhaust after-treatment
1	X	1998	Petrol	1.4	MPI	Natural	Electronic	No	TWC
2	Y	2002	Petrol	1.8	MPI	Natural, variable valve timing	Electronic	No	TWC
2	Z	2002	Petrol	1.6	Lean DI	Natural	Electronic	Yes	TWC + NO_x trap
1	A	1997	Diesel	1.9	IDI	Natural	Distributor, mechanical	Yes	None
1	B	1993	Diesel	2.5	IDI	Natural	In-line, mechanical	Yes	Oxidation catalyst
1	C	1997	Diesel	1.9	DI	TC/Intercooler	Distributor / Electronic	Yes	Oxidation catalyst (close coupled)
1	Acat	1997	Diesel	1.9	IDI	Natural	Distributor, mechanical	Yes	Oxidation catalyst
2	D	2002	Diesel	1.9	DI	TC/Intercooler	Unit injectors	Yes	Oxidation catalyst
2	E	2001	Diesel	2.2	DI	TC/Intercooler	Common rail	Yes	DPF

Emission factors 2009: Report 5 – a review of the effects of fuel properties on road vehicle emissions

TRL was commissioned by the Department for Transport to review the approach used in the National Atmospheric Emissions Inventory (NAEI) for estimating emissions from road vehicles, and to propose new methodologies. This Report describes the effects of fuel properties on exhaust emissions. The main topics covered in the Report are: (i) the effects of fuel sulphur content on exhaust emissions; (ii) the effects of other fuel parameters; (iii) the effects of biofuels; (iv) the modelling of fuel effects; and (v) the implications in terms of the UK emission factors. The reduction in fuel sulphur content from 50 ppm (“ultra-low sulphur”) to 10 ppm (“sulphur-free”) seems unlikely to bring substantial emission benefits for current Euro 3/III and 4/IV vehicles. The main exception may be PM emissions. It is possible that older petrol vehicles could show some degree of catalyst recovery (i.e. lower emission levels) when used on sulphur-free fuel. However, such effects are rather difficult to quantify as there seems to be little interest in testing old vehicles on new fuels. Changes in other fuel properties can also result in small, but sometimes significant, changes in emissions. In order to derive fuel composition scaling factors, an adapted version of the method presented in COPERT III/4 is proposed. Fuel composition scaling factors are given for all light-duty and heavy-duty vehicles, and these should be used in conjunction with the emission factors which have been derived in the project. From the evidence it appears that emission scaling factors for biodiesel and ethanol are not required in the UK.

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Price code: 3X

ISSN 0968-4093

ISBN 978-1-84608-819-3

9 781846 088193

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