



Emission factors 2009: Final summary report

by P G Boulter, T J Barlow, I S McCrae and S Latham

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Executive Summary

TRL Limited 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 summarises the work conducted on the project. The Report covers three different types of source: hot exhaust emissions, cold-start emissions and evaporative emissions, with most of the work focussing on hot exhaust emissions. Some of the main findings are summarised below.

Hot exhaust emissions

Driving cycles and test parameters

A review was undertaken of the methods used to determine emission factors for use in the UK. The review focussed on the driving cycles used in emission tests and the parameters recorded, and included the compilation of a 'Reference Book of Driving Cycles'. For all vehicle categories it was concluded that more representative driving cycles should be considered for future testing. In addition, urban buses and coaches should be treated separately when deriving emission factors. When compiling an emission factor database, correction factors should ideally be applied to account for, for example, the gear-shift strategy, vehicle mileage and ambient air temperature. Although there appears to be little justification for routinely including continuous emission measurements in the tests used for emission factor development, these may be beneficial for the evaluation of technical and/or policy measures.

Modelling of emissions

Various average-speed and traffic situation models were compared with the NAEI model. Generally, there was a very good agreement between the shapes of the emissions curves in the NAEI and the various models tested, but the results varied with vehicle category and pollutant. Four types of assessment were considered in an attempt to determine the accuracy of the predictions of different models. These involved the comparison of model predictions with (i) on-board emission measurements, (ii) remote sensing measurements, (iii) the results from the inversion of an air pollution model and (iv) measurements in road tunnels. The assessments included errors, assumptions and limitations which made it difficult to make general conclusions. Nevertheless, the results of the assessments indicated that the current UK emission factors probably provide a reasonably accurate characterisation of *total* emissions from road transport. It was therefore concluded that there is little justification at present for changing the current emission calculation method in the NAEI, but the emission factors for specific vehicle categories should be improved where possible. Further efforts are also required to categorise vehicles appropriately and to characterise operational conditions (such as road gradient and load).

Effects of fuel properties

Two aspects of fuel sulphur content were reviewed: (i) the effects of switching from 'ultra-low sulphur' (50 ppm) fuels to 'sulphur-free' (10 ppm) fuels and (ii) 'catalyst recovery' associated with sulphur-free fuel. The reduction in fuel sulphur content to 10 ppm seems unlikely to bring substantial emissions benefits for Euro 3/III and 4/IV vehicle technologies. 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.

The effects on exhaust emissions of two main types of biofuel were also reviewed: biodiesel blends and ethanol blends. 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 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 in the UK is not predicted to exceed 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 with vehicles using older technologies.

New emission factors

New hot exhaust emission factors were developed for road vehicles in the UK. Emission data for light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) from many European test programmes were used in the project. For regulated pollutants, the LDV emission factors were developed for vehicles complying with emission standards from pre-Euro 1 to Euro 6 (assumptions were required for Euro 5 and Euro 6 vehicles).

The CO₂ emission functions took into account the reduction in emissions from new cars. For HDVs the average-speed emission factors from the ARTEMIS project were taken as the basis for the UK emission factors. The emission factors for mopeds were taken from the COPERT 4 model, and those for motorcycles were taken from the ARTEMIS project. Emission factors were also developed for the following unregulated pollutants: methane (CH₄), 1,3-butadiene, benzene, nitrous oxide (N₂O), ammonia (NH₃), polycyclic aromatic hydrocarbons (PAHs) and nitrogen dioxide (NO₂).

New scaling factors

Scaling factors for different years were developed to account for mileage effects relating to vehicle samples and fuel composition effects. 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.

Model demonstration

The emission factors and scaling factors for hot exhaust emissions were demonstrated in a number of spreadsheets.

Cold-start emissions

During the project consideration was given to a number of potential sources of data and models which might be used to update and refine the NAEI approach for estimating cold-start emissions. The ARTEMIS cold-start models for passenger cars represent the state-of-the-art at the present time. However, discussions relating to the implementation of the ARTEMIS cold-start model in national inventories are still in progress. The main conclusion was that before any more detailed modelling of cold-start emissions is attempted the current NAEI model ought to be updated to reflect the COPERT 4 methodology. However, the compilers of COPERT are currently improving the methodology for cold-start emissions. In addition, other new cold-start models ought to be available in 2009. When these are published they should be considered for inclusion in the NAEI.

Evaporative emissions

The NAEI approach for evaporative emissions is based largely on the COPERT II and COPERT III models, combined with supporting experimental data from before 1995. Comparisons between the NAEI, ARTEMIS and draft COPERT 4 models are summarised. The main conclusion of this work is that, given that considerable effort has been put into developing the new method in COPERT 4 and the flexibility it offers, there would be sufficient justification for changing the NAEI to include this method.

1 Introduction

1.1 Background

Emissions of air pollutants in the United Kingdom are reported in the National Atmospheric Emissions Inventory (NAEI) (Dore *et al.*, 2008). 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 reduce UK emissions. Projections from the road transport model in the NAEI are used to assess the potential benefits of policies and future emission standards for new vehicles. It is therefore essential that the model is as robust as possible and based on sound data.

Some information on the NAEI methodology is available from the NAEI web site¹, but the most detailed description is provided in the UK annual report of greenhouse gas emissions for submission under the United Nations Framework Convention on Climate Change (Choudrie *et al.*, 2008).

TRL Limited was commissioned by the Department for Transport (DfT) to review and propose revisions and updates to the NAEI methodology for road transport, and to address the main weaknesses in the modelling approach.

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 Report (and others produced for the project).

It should also be noted that, in accordance with the emission legislation, a slightly different notation is used in the Report to refer to the emission standards for light-duty vehicles (LDVs)², heavy-duty vehicles (HDVs)³ 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.*).

1.2 Potential weaknesses in the NAEI model

Recent UK and European Union (EU) research projects on road transport emission modelling have identified potential weaknesses in the types of methodology used in the UK. There are also some areas of the NAEI road transport model which are based on rather old data and ought to be updated. In the following Sections specific weaknesses are identified in relation to the various types of emission source associated with road vehicles.

1.2.1 Hot exhaust emissions

'Hot' exhaust emissions are produced by a vehicle when its engine and exhaust after-treatment system are at their normal operational temperatures. The temperature of engine coolant during normal operation is typically between around 70°C and 90°C, whereas the temperature of the exhaust system reaches several hundred degrees centigrade. Hot exhaust emission factors for various categories of vehicle and pollutant - as used in the NAEI - are currently given in the UK Emission Factor Database (UKEFD). During 2002, an updated version of the database, containing emission functions for carbon monoxide (CO), total hydrocarbons (HC), oxides of nitrogen (NO_x), PM₁₀⁴, benzene, 1,3-butadiene and carbon dioxide (CO₂), and functions describing fuel consumption, was prepared by TRL and NETCEN. The database included existing measurements from an earlier version of the database, data from the EC MEET⁵ project, and a new set of measurements reported by TRL (Barlow *et al.*, 2001). With the exception of CO₂, the emission functions for the pollutants covered in the 2002 UKEFD are identical to those given in the procedure for air pollution estimation in Volume 11 of the

¹ <http://www.naei.org.uk/>

² 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.

³ Heavy-duty vehicles are all vehicles heavier than 3.5 tonnes, including heavy goods vehicles (HGVs), buses and coaches.

⁴ PM₁₀ = particulate matter with an aerodynamic diameter of less than 10 µm.

⁵ MEET = Methodology for calculating transport emissions and energy consumption (European Commission, 1999).

Design Manual for Roads and Bridges (DMRB) (Highways Agency *et al.*, 2007). The 2002 UKEFD is still used as the basis for a wide range of emission and air pollution modelling studies in the UK.

A number of specific weaknesses in the 2002 database were identified by Boulter *et al.* (2005), including the following:

- *Robustness of the existing emissions data*
 - There are very few test results for Euro 3 cars.
 - The measurements on Euro 2 LGVs are very limited.
 - The measurements on Euro I and Euro II HGVs and buses are limited.
 - There is little information on emissions from motorcycles.
- *Coverage of vehicle types and fuel types*
 - There are no emission measurements for Euro 4 cars.
 - There are no emission measurements for Euro 3 and Euro 4 LGVs, and Euro III/IV HGVs and buses.
 - There are no emission functions for vehicles running on fuels other than petrol or diesel (*e.g.* CNG, LPG), and for certain engine technologies (*e.g.* petrol direct-injection).
 - There are no emission functions for post-Euro 4/IV vehicles of all types.
 - No information is provided on the effects of specific after-treatment technologies, such as particulate traps, selective catalytic reduction, *etc.*
- *Coverage of pollutants*

Only a small number of unregulated compounds are covered, with the emission functions being based on very limited measurements and various assumptions.
- *Coverage of operational conditions*
 - The emission functions do not include the effects of ancillary equipment, variations in vehicle load, or road gradient.
 - There are few emission measurements for very low speeds (*i.e.* less than 5 km h⁻¹), very high speeds (*i.e.* greater than 130 km h⁻¹) and idling (0 km h⁻¹).

The following limitations are also worth noting:

- There is an absence of detailed methods for taking fuel properties ('fuel quality') into account.
- Although some effort is made in the NAEI to assess the uncertainty in the road transport emission estimates, the reported assessment is somewhat lacking in detail.
- There are also considered to be a number of issues associated with the average-speed modelling approach used in the NAEI.

1.2.2 Cold-start emissions

The emissions produced during the vehicle warm-up phase are often referred to as 'cold-start' emissions. For some pollutants a large proportion of the total emission from road transport, especially in urban areas, is due to vehicles being driven under cold-start conditions. In the NAEI cold start emissions are estimated using the COPERT II methodology. This uses assumptions relating to average trip length, average ambient temperature, and the ratio of cold-start emissions to hot emissions. However, the data used to generate the emission factors are now rather old, and may no longer be representative of modern vehicles. COPERT itself is being updated in 2009, and other models which use more sophisticated approaches and incorporate more recent data are also available.

1.2.3 Evaporative emissions

Evaporation from petrol vehicle fuel systems makes a significant contribution to emissions of volatile organic compounds (VOCs). Evaporative emissions are modelled in the NAEI using data from studies by CONCAWE (1987), Barlow (1993) and ACEA (1995), which characterise evaporative emissions from vehicles both with and without emission controls. Again, these data and methodologies are rather old and are due for revision.

1.2.4 Non-exhaust PM emissions

There are currently no EU regulations specifically designed to control non-exhaust emissions of particulate matter (PM) from road vehicles, such as those arising from tyre wear, brake wear, road surface wear and the resuspension of material previously deposited on the road surface. As exhaust emission-control technology improves and traffic levels increase, the proportion of total PM emissions originating from uncontrolled non-exhaust sources will increase. Furthermore, the data relating to the emission rates, physical properties, chemical characteristics, and health impacts of non-exhaust particles are highly uncertain. Although a method is used in the NAEI for estimating non-exhaust PM, the emission factors are not currently included in the UKEFD. However, non-exhaust emissions were outside the scope of this project.

1.3 Project objectives

The overall purpose of this project was to propose complete methodologies for modelling road transport emissions in the UK, with the identification of approaches which could improve the quality of the NAEI model and areas where existing methodologies gave good quality estimates and could be retained.

The specific objectives of the project took the form of a list of Tasks:

- Task 1: Reviewing the methods used to measure hot exhaust emission factors, including test cycles and data collection methods (Boulter *et al.*, 2009a).
- Task 2: Reviewing the use of average vehicle speed to characterise 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, 2009a).
- Task 5: Reviewing the effects of fuel quality on vehicle emissions (Boulter and Latham, 2009b).
- 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 (this Report).
- Task 9: Final report (this Report).

This Report summarises the work conducted on the project. For more information on the specific tasks, the reports mentioned above should be consulted.

1.4 Report structure

The Report is structured according to the different types of source associated with road vehicles. The remaining Chapters are therefore arranged as follows:

Chapter 2: Hot exhaust emissions

Chapter 3: Cold-start emissions

Chapter 4: Evaporative emissions

As noted earlier, emissions of non-exhaust particulate matter were outside the scope of the project

The emission factors for hot exhaust emissions were demonstrated in a number of spreadsheets, as described in Chapter 5. Chapter 6 summarises the main conclusions and recommendations from the work.

2 Hot exhaust emissions

2.1 Background

Most of the work undertaken in the project related to hot exhaust emissions. This Chapter of the Report summarises this work, with particular reference to the following topics:

- The methods which are used for determining emission factors.
- The models which are available for estimating emissions.
- The effects of fuel properties on emissions.
- New emission factors for use in the UK.
- New emission scaling factors for use with the new emission factors.

2.2 Methods for determining emission factors

A review was undertaken of the methods used to determine hot exhaust emission factors for use in the UK. This required that consideration be given to the emission measurement process. This work - described in the Report by Boulter *et al.* (2009a) - featured two main elements: (i) an evaluation of the driving cycles used in emission tests and (ii) a review of the parameters recorded during emission tests.

2.2.1 Evaluation of driving cycles

An assessment was undertaken of the driving cycles used in the development of the 2002 UKEFD. The assessment involved two main stages:

- (i) The compilation of a driving cycle 'Reference Book' in order to characterise driving cycles in a systematic manner for use within the project (Barlow *et al.*, 2009).
- (ii) A quantitative investigation of the extent to which the cycles currently used in the UKEFD and the cycles commonly used in recent emission test programmes represent the range of driving conditions experienced on UK roads.

Reference Book of Driving Cycles

Large numbers of driving cycles have been developed around the world in order to characterise emissions from road vehicles. These include:

- Specific cycles for different types of vehicle (*e.g.* cars, light goods vehicles, buses).
- Specific cycles for different levels of engine power.
- Cycles which are representative of driving in different types of area or on different types of road.
- Legislative cycles from different countries.
- Constant-speed cycles.
- Cycles used to evaluate aspects such as traffic management, eco-driving and gradient effects.

In Europe alone hundreds, if not thousands, of different driving cycles have been used. However, the vast majority of emission tests have been conducted over a relatively small number of these cycles - most notably the driving cycles defined in legislation.

Prior to the project there was no single document which comprehensively described all these cycles. The first activity was therefore the compilation of a Reference Book of Driving Cycles (Barlow *et al.*, 2009). A total of 256 driving cycles are presented in the Reference Book, and a large number of statistical descriptors are given for each cycle. The Reference Book was designed primarily for use by TRL within the DfT project, although it is also hoped that it will be a useful source of information for other researchers and practitioners in the fields of vehicle emissions and air pollution.

Evaluation of driving cycles

Comparisons were made between the characteristics of several sets of data relating to vehicle operation:

- (i) A large database of real-world driving patterns recorded for vehicles in normal operation on UK roads.
- (ii) The Reference Book containing 256 driving cycles from various countries.
- (iii) The driving cycles in the 2002 UKEFD.
- (iv) The WSL⁶ driving cycles for cars and vans.
- (v) The FiGE sub-cycles⁷ for heavy-duty vehicles.
- (vi) The set of driving cycles for passenger cars developed within the ARTEMIS project.

The data sets were initially compared with the speed statistics for vehicle types and road types in Great Britain (Department for Transport, 2005). The national statistics indicate that relatively few vehicles on UK roads are travelling at speeds below 20 mph. This implies that for emission inventories the accurate characterisation of emissions at very low speeds is likely to be less important than accurate characterisation at other speeds. However, accurate emission factors at low speeds remain important for local air quality assessment purposes. Furthermore, the national statistics showed that significant number of cars on the road (56% on motorways and 48% on dual-carriageways) are travelling at speeds which are higher than the maximum average speed of the WSL cycles (112 km h⁻¹), and therefore emissions from such cars are not routinely covered in emission test programmes. One area of concern is therefore extent to which the driving cycles currently used for emission measurement cover the higher speeds in the UK.

In a more detailed assessment the characteristics of data sets (ii) to (vi) were compared with the characteristics of the real-world driving patterns in data set (i). This assessment was conducted using an existing tool - the *Art.Kinema* program - which was produced as part of the ARTEMIS project (De Haan and Keller, 2003). *Art.Kinema* computes a wide range of descriptive parameters (more than 30) for a user-defined driving cycle. However, the descriptive statistics used in the comparisons were limited to average cycle speed, standard deviation of speed, average positive acceleration and average negative acceleration. The results are summarised by vehicle type below.

Cars and LGVs

For cars, the real-world driving patterns, the Reference Book driving cycles and the UKEFD cycles had broadly similar average speed distributions. The real-world driving patterns had average speeds ranging from just above zero to around 118 km h⁻¹. However, the upper limit was artificially low as drivers were instructed to obey speed limits, and it is clear that much higher speeds can actually occur. The driving cycles in the Reference Book and UKEFD covered a similar range of average speeds, but had a maximum average speed of 130 km h⁻¹. Some of the low-speed Reference Book/UKEFD driving cycles were found to have relatively high average accelerations and average decelerations which were not apparent in the real-world driving patterns.

The WSL cycles, which have been routinely used to measure emissions in UK test programmes, covered much of the speed range observed in the driving patterns (notwithstanding the 'artificial' limit for the latter). The WSL cycles were also generally less 'aggressive' than driving patterns in the real world. In contrast, the ARTEMIS sub-cycles were generally slightly more 'aggressive'. On the whole, the characteristics of the real-world driving patterns appeared to be well-represented in the UKEFD as a whole.

For LGVs, the real-world driving patterns had only relatively low average speeds, and so comparisons with the driving cycles were inconclusive, although the assessment of cycle dynamics again indicated that the WSL cycles were less aggressive than the real-world driving patterns, the driving cycles in the Reference Book and the UKEFD cycles.

There are a number of possible explanations for these observations relating to the WSL cycles. For example, the driving patterns used to develop the WSL cycles were logged using a variety of vehicles, ranging from small, low-powered cars to large, powerful cars, and the driving pattern data were then analysed to produce a

⁶ WSL = Warren Spring Laboratory. The 'Congested Traffic' 'Urban', 'Suburban', 'Rural' and 'Motorway' cycles developed by WSL have been used extensively in the UK for conducting emission tests.

⁷ The FiGE cycle is the chassis dynamometer simulation of the European legislative test cycle for heavy-duty engines - the European Transient Cycle (ETC). This has also commonly been used for testing heavy-duty vehicles in DfT research programmes. The FiGE cycle has three sub-cycles ('urban', 'suburban', 'motorway').

set of average cycles which were suitable for all cars. These average cycles were subsequently adjusted on a chassis dynamometer, and gear-change points added to produce three different cycles for small, medium and large cars (the speed traces remained very similar). In addition, the driving patterns were recorded using a single driver who was experienced in the test routes used. The other test programmes at TRL have used a variety of drivers – mainly TRL staff of various age and driving experience and also external drivers. The differences may therefore be due to different driving styles of the various drivers.

HGVs

The FiGE cycle has been routinely used in the UK to measure emissions from heavy-duty vehicles, but there are some questions concerning its usefulness for emission factor development. Firstly, although some of the real-world driving patterns, the Reference Book driving cycles and UKEFD cycles have average speeds lower than 10 km h^{-1} , such low average speeds are not represented in the FiGE cycle. Secondly, for large modern HGVs the speed covered by the motorway FiGE cycle is similar to the maximum speed which can be achieved, but some older small HGVs (pre-October 2001, < 7.5 tonne GVW) are not required to be fitted with a speed limiter, and their speeds are significantly higher. The national statistics show that on motorways 40% of two-axle rigid HGVs exceed 97 km h^{-1} . The FiGE cycle does not cover these higher speeds, but this is not likely to represent a significant problem as the number of unrestricted vehicles on the road will decrease with time. Thirdly, the higher-speed FiGE cycles appeared to have lower average accelerations and decelerations than the real-world driving patterns.

Again, some of the low-speed Reference Book/UKEFD driving cycles were found to have relatively high average accelerations and average decelerations which are not apparent in the real-world driving patterns.

Buses and coaches

In the UKEFD all buses and coaches are treated as a single class of vehicle. However, due to their different operating characteristics, it would be more useful to consider these vehicles as two distinct groups. In addition, previous tests have shown that some buses are unable to meet the speeds of the motorway FiGE cycle. Therefore, bus-specific cycles should be used when measuring emissions.

The Reference Book driving cycles had a similar average speed distribution to the real-world driving patterns. However, the distributions for the UKEFD cycles and the FiGE cycles were biased towards higher speeds. The UKEFD and FiGE cycles also clearly had lower accelerations and decelerations than the real-world driving patterns and the driving cycles in the Reference Book.

2.2.2 Review of emission test parameters

The second main element of this part of the Project was a review of the parameters and data recorded during emission tests. The objective was to provide recommendations relating to how the usefulness of the recorded data might be improved, and which information should be routinely measured during testing.

Emissions data can be recorded using a number of different methods, under different ambient conditions, and in different formats. Examples of parameters which can vary from laboratory to laboratory, and from programme to programme, include the length, alignment and temperature of exhaust sample lines, the dynamometer fan height and speed response, the types of analyser used, the recording frequency of measurements, and the temperature, pressure and humidity of the ambient air. It is recognised that many such parameters affect emission measurements, but their actual impact on the results has not been well quantified. This is especially true for cars equipped with new technology engines and emission control systems. Emissions from these vehicles can be very low, but can also be very sensitive to changes in test conditions. This undermines the production of accurate emission factors (Joumard *et al.*, 2006a).

In order to understand real-world emissions it is important to determine how variations in sampling conditions affect emission measurements. For cars, probably some of the most comprehensive examinations of the effects of different emission test parameters were those conducted as part of the ARTEMIS project (Joumard *et al.*, 2006a, 2006b) and the PARTICULATES project (Samaras *et al.*, 2005). The results and conclusions from these studies are summarised below.

Cars

In the MEET project and the COST 319 Action, emission factors were developed using existing data in Europe (European Commission, 1999). However, one of the main conclusions was that there were large differences between the emission levels measured at different laboratories and within individual vehicle categories. In order to produce accurate emission factors for current and near-future vehicle technologies, a two-fold strategy was therefore adopted in ARTEMIS:

(i) *An investigation of the measurement differences between laboratories*

Although many of the parameters influencing emission measurements are well known, their actual effects have not been well quantified. The ARTEMIS test programme was designed according to the following requirements:

- Specific vehicle models had to be selected according to their contribution to the fleet population.
- Vehicles had to be tested over cycles which covered a wide range of real-world operation.
- The effects of mileage and the deterioration of emission-control equipment had to be investigated in more detail.
- The systematic differences between laboratories had to be examined in detail.

(ii) *Investigating, understanding and modelling the emission differences between comparable vehicles*

In MEET, large differences were observed between the emission levels of cars which were compliant with the same emission standard, were of the same size, had more or less the same mileage, and were operated over similar driving cycles. Again, these differences were found to be much more pronounced for the most recent vehicles (Euro 2 at the time). The analyses and data from a number of investigations conducted prior to ARTEMIS indicated that the reasons for these differences included the following:

- Emission levels which were close to the detection limits of analysers.
- Different engine management and emission control concepts.
- Different responses to driving cycles (*e.g.* speed, acceleration, engine load, idle time).
- Differences in mileage, age and level of maintenance.
- Differences in other parameters, such as the test conditions, laboratory, *etc.*

The ARTEMIS work led to a new methodology for estimating emissions factors for passenger cars. On the basis of the above, the main objectives of the work were:

(i) *To study the sensitivity of pollutant emissions to key parameters*

These parameters were divided into four main categories:

- Driving behaviour parameters, such as the driving cycle and the gear-shift strategy.
- Vehicle-related parameters, such as the engine management and emission control concept, the emission stability, mileage, age, maintenance level, and fuel properties.
- Vehicle sampling parameters, such as the way in which test vehicles are chosen by a laboratory and the number of vehicles tested in each category.
- Laboratory-related parameters, such as the ambient test conditions, the dynamometer settings and the analytical equipment used.

Some of these issues were addressed via reviews of the literature, or by the processing of existing emissions data. For others, new laboratory measurements were required.

(ii) *To develop methods which allow the harmonisation of European emission measurements*

This involved establishing 'standard' conditions in order to obtain comparable data, and building methods to extend the data to any European condition. The approach was designed to improve the accuracy of European emission models, and to greatly enlarge the range of application for such models.

A reference set of real-world driving cycles was developed in order to improve the representativeness of emission tests and the comparability of the measurements made in different laboratories. Three main real-world driving cycles - 'urban', 'rural', and 'motorway' - were constructed to represent driving according to the respective area/road types. Two versions of the motorway cycle were produced, one with a maximum speed of

150 km h⁻¹ and one with a maximum speed of 130 km h⁻¹. The latter was developed for use on emission testing facilities which are not capable of operating at the higher speed. Some of the cycles also included a 'pre-' or 'post-' phase to allow trip start and end conditions to be defined. Different gear-shift strategies were also reviewed, with a simplified approach being adopted for ARTEMIS (André, 2004).

Emission tests were conducted at each of the nine participating laboratories using a chassis dynamometer. The fuels used during the tests were obtained from local petrol stations. The regulated pollutants (CO, HC, NO_x and PM) and CO₂ were collected using a constant volume sampler (CVS). Pollutants were collected as bag or filter samples, and were also usually measured continuously. Standard analytical techniques were used (NDIR for CO and CO₂, chemiluminescence for NO_x, flame ionisation detection for HC, and filter weighing for PM), fuel consumption was calculated using the carbon balance method.

Various parameters were investigated, with a separate test programme being designed for each parameter. It was also considered necessary to compare the laboratories by performing a 'round robin' test with a single reference vehicle. A total of 183 vehicles were tested during the ARTEMIS project. The detailed characteristics of all the test vehicles are given by Joumard *et al.* (2006a). In total, 2,753 tests were carried out, of which:

- 537 tests examined the influence of driving behaviour.
- 1,334 tests examined the influence of vehicle parameters.
- 672 tests examined the influence of laboratory-related parameters.
- 210 tests were conducted during the round robin exercise.

During the test programme, it was found that some parameters did not exert an influence over the measured emission factors. For other parameters, an influence was apparent, but could not be quantified. Finally, some parameters had a clear and quantifiable influence.

There was no statistically significant influence on emission measurements for the parameters listed in Table 1. This does not mean that these parameters have no influence on the emission measurements, but only that there is no currently known influence, taking into account the small data sample or the contradictory results. The parameters having a qualitative influence are summarised in

Table 2. In the case of parameters having a clear, statistically significant and quantifiable influence on emissions (Table 3), it was possible to normalise emission measurements from different laboratories using correction factors.

Table 1: Parameters having no influence on emissions (Joumard *et al.*, 2006a).

Parameter		Findings	Recommendation
Vehicle-related parameters	Emissions stability	The differences between the test results of several vehicles were larger than the differences obtained when testing the same vehicle several times.	A limited number of repeat tests should be conducted on each test vehicle, rather than taking a smaller sample of vehicles and using many repeat tests.
	Fuel properties	In spite of observing significant differences, especially for PM emissions with diesel vehicle, it was not possible to propose an explanation based on the today knowledge of fuel effect.	Common fuels should be used, rather than separate laboratory fuels in different countries.
	Cooling fan operation	Although the cooling arrangement did affect the emissions, the results proved to be inconclusive. The position of the vehicle bonnet (either open or closed), the height of a small blower, and the cooling power (<i>i.e.</i> the flow speed of the cooling air) have no clear influence on the measured emissions.	A high-power cooling system should be used in order to reproduce, as far as possible, real-world cooling.
Laboratory-related parameters	Sample line temperature	The observed emission changes contradicted what was expected from the physio-chemical properties of the diluted emissions.	None
	PM filter preconditioning	No significant effects of the filter preconditioning were observed.	None
	Dilution air conditions	The quality of the dilution air has not a significant influence on emission measurements	None

Table 2: Parameters having a qualitative influence on emissions (Joumard *et al.*, 2006a).

Parameter		Findings	Recommendation
Driving cycle parameters	Influence of the driver	Only CO ₂ emissions were significantly higher with a human driver than with a robot driver, but the difference could not be explained by the driving characteristics. The robot did not give more stable emissions, and some driving cycles are too aggressive for it.	A human driver can be used for emission tests. Tolerances of $\pm 2 \text{ km h}^{-1}$ and $\pm 1 \text{ s}$ should be applied. A test should be accepted if it is within these bands for > 99% of the time, and if the driven distance is within 1% of the reference distance. Notes should be made of failures due to insufficient power, wheel slip, <i>etc.</i> , or if the engine stalls. In all other cases a test should be rejected.
Vehicle-related parameters	Technological characteristics	The type approval category and the fuel have a clear influence on the emissions, and the engine capacity in some cases. No correlations between emission behaviour and specific emission control technologies were found within the same type approval category.	The addition of specific technological characteristics to models will not improve the accuracy of emission databases for conventional cars up to Euro 4
	Vehicle preconditioning	The preconditioning conditions have an influence in some cases, but rarely for modern close-loop vehicles.	A 10-minute cycle at a constant speed of 80 km h ⁻¹ can be considered as the most suitable preconditioning cycle.
Vehicle sampling method	Method of vehicle sampling	Vehicles routinely taken from hire companies – therefore relatively new and well maintained.	Where possible, test vehicles should be selected from an 'official' list. The real-world distributions of fuels, emission standards, vehicle size, maximum engine power, mileage should be taken into account in the selection of vehicles.
	Vehicle sample size	The variability between vehicles is a significant factor, together with the emitter status. It is not possible to know the emitter status before measurement, and the high variability between vehicles of a same category requires that cars are samples randomly within a category.	A minimum sample of 10 vehicles should be used to derive emission factors for a given vehicle category which are representative of an average vehicle behaviour.
Laboratory-related parameters	Dynamometer settings	The dynamometer settings have a clear influence on all emissions, but are only significant for CO ₂ and fuel consumption, and on NO _x for diesel vehicles. Although only few effects were found significant, they still require an accurate simulation of the actual road load.	It is recommended that emissions measured with altered chassis dynamometer settings are not used to derive emission factors. For emission factor development, road load information derived from the coast-down method performed by the laboratory and inertia setting should be as close to the on-road values as possible.
	Response time	Signals not always correctly adjusted in earlier test programmes.	In the development of instantaneous emission models, the emission signals must be corrected for dynamic distortion during measurement.

Table 3: Parameters having a quantitative influence on emissions (Joumard *et al.*, 2006a).

Parameter		Findings
Driving cycle parameters	Driving cycle	The driving cycle has a significant effect on emissions, but it was not possible to design a systematic correction function. However, given the very high diversity of the emission data collected in ARTEMIS, and the large range of the corresponding driving cycles, it was not possible to develop emissions factors without managing this cycle influence. A harmonisation approach was developed, based on the similarities between cycles from a kinematic perspective. This enabled the grouping of the hot emission data into coherent groups.
	Gear-shift behaviour	It was possible to classify gear-shift strategies according to CO ₂ emissions (the only pollutant systematically affected). The most polluting strategy was one in which gear changes were defined for given engine speeds. The least polluting strategy was one in which gear changes were defined for given vehicle speeds.
Vehicle-related parameters	Emission degradation	The influence of mileage on petrol-fuelled vehicle emissions depends on the pollutant, the type approval category (or emission standard) and the average speed. Mileage has no influence on CO ₂ emissions, but increases CO, HC and NO _x emissions of petrol cars: Between 0 km and 100,000 km, these emissions increase by a factor 3.6 in average for Euro 1 and 2 vehicles, and by 15% for Euro 3 and 4 vehicles. No mileage effect was observed for diesel vehicles. No effect of maintenance was observed on the emission level, either as a consistent before-after maintenance improvement or as a function of mileage.
Laboratory-related parameters	Ambient temperature	An ambient temperature effect was observed for all pollutants and most vehicle classes.
	Ambient humidity	The influence of the ambient humidity was observed only for NO _x and for some vehicle classes.
	Dilution ratio	A higher dilution ratio increases only diesel PM emissions.

HDVs

Although HDVs were studied in great detail in ARTEMIS, the investigation of emission test parameters was less extensive than that for cars, and there was no round-robin programme. Nevertheless, information was obtained on a number of different parameters which are important for emission factor development. The conclusions drawn from the ARTEMIS work on HDVs (Rexeis *et al.*, 2005) included the following:

- Existing formulae can be used to predict, with reasonable accuracy, the changes in emissions due to different fuel properties, although the effects are actually rather small.
- HDVs exhibit stable emissions behaviour during their lifetimes. However, this may change with the introduction of much more sophisticated technologies in the near future.
- Since the introduction of the Euro I standard, NO_x emission levels for real-world driving conditions have not decreased as much as might have been predicted from the type approval limits. The main reason for this is the more sophisticated technologies being used for engine control and fuel injection, which allow different specific optimisation over different regions of the engine map.
- High fuel efficiency has a much higher market value than low real-world emissions. Since the market situation encourages manufacturers to optimise fuel consumption wherever possible, the old ECE-R49 type approval test was not able to guarantee low NO_x emissions for the new generation of electronically controlled engines (post 1996). This situation improved with the introduction of the ESC test for Euro II.
- Since engine technology has progressed quite rapidly since 1996, it cannot be guaranteed that the combination of the ESC and ETC cycles in the current type approval test will prevent real-world emission levels being significantly higher than at type approval (off-cycle optimisation). Thus, the type approval limits and the type approval test procedure have to be well balanced to produce cost-effective benefits for air quality. Only lowering the limit values clearly gives an incentive to introduce off-cycle optimisation.
- The emission behaviour of Euro V (and later) vehicles is hard to predict since the technologies used are new and no production vehicles with these technologies were available for measurements. It is expected that in-use tests will be necessary to prevent emission levels during real-world driving exceeding the type approval values.
- Due to the large and non-linear effects on emissions of vehicle size and vehicle load, as well as the effects of the driving cycle and the road gradient, the use of simple correction factors for these model parameters, in combination with speed-dependent regression functions for the basic emission factors, is not recommended where high accuracy is required.

Two-wheel vehicles

The ARTEMIS work on two-wheel vehicles is summarised by Elst *et al.* (2006). An extensive measurement programme was conducted, involving tests on 90 motorcycles. A round robin test programme was conducted to check whether the results over different driving cycles were reproducible when in different laboratories, and to identify potential measurement difficulties. The sensitivity of emissions to fuel properties and inspection and maintenance was also examined. This work is relevant to the development of emission factors for two-wheel vehicles in the UK. The conclusions drawn from the ARTEMIS work included the following:

- When real-world passenger car and motorcycle driving were compared, the main differences were at higher average speeds. At higher speeds the driving of two-wheel vehicles is much more dynamic than that of passenger cars due to the relatively high power:mass ratio.
- The ARTEMIS cycle for passenger cars is very dynamic, and for urban driving has appropriate acceleration values for motorcycles.
- NO_x emissions from two-wheel vehicles were very low over the type approval cycle.
- For motorcycles having high CO and HC emission results, the differences between the results over the type approval and real-world cycles were negligible. As emission levels over the type approval test decrease, the differences increased. However, this conclusion was not valid for NO_x. Some of the tested motorcycles were equipped with an exhaust system configuration which appeared to have been specifically calibrated for the type approval cycle.
- Emissions over the ARTEMIS urban and rural parts were higher than emissions over the FHB test cycles, and it appeared that the differences were related to driving dynamics. However, for motorcycles equipped

with exhaust gas after-treatment systems (Euro 3), driving dynamics appears to be a less reliable determinant of emissions.

- For the measurements in ARTEMIS a Hungarian market fuel and a fuel meeting the WWFC Category 4 future requirements were selected. With regard to replacing market fuel by fuel that is compliant with WWFC4 requirements:
 - CO emissions were, on average, reduced by 15%,
 - HC emissions decreased by 5%,
 - NO_x emissions were not affected.
 - CO₂ emissions increased by 4%.
 - Fuel consumption was not affected.
- The effects of inspection and maintenance ranged from an adverse effect (emission increase after maintenance) for all pollutants of one of the motorcycles (range -18% to -1%) to very high for two motorcycles which had a faulty battery (range 299% to 10%). The effect of inspection and maintenance on emissions may therefore not be neglected. Although measurements were carried out before and after maintenance for seven motorcycles, the effect was dependent on the type of maintenance that was conducted. Therefore, average adjustment factors were derived to address the effects of inspection and maintenance on emissions.

2.3 Models for estimating hot exhaust emissions

2.3.1 Background

The current UK emissions factors for regulated pollutants, and for some unregulated pollutants, are defined as functions of average vehicle speed over a trip. Barlow and Boulter (2009) reviewed the use of average vehicle speed to characterise hot exhaust emissions, based upon comparisons with other models. In addition, a number of different approaches were used to evaluate the accuracy of the NAEI method and emission factors, including model comparisons, reviews of model validation studies such as tunnel measurements and inverse modelling, and reviews of uncertainty analysis studies.

2.3.2 Model comparisons

Several models were identified as being potentially useful for the revision of the NAEI, based on aspects such as availability, cost, coverage of pollutants and vehicle categories, robustness, and ease of use. The following models were compared with the NAEI:

- COPERT III⁸ - average speed model
- ARTEMIS (V3b) - average speed model
- ARTEMIS (V3b) - traffic situation model
- HBEFA (V2.1) - traffic situation model
- VERSIT+ - multiple regression model

The instantaneous models MODEM⁹ (Joumard *et al.*, 1995; Barlow, 1997) and PHEM¹⁰ (Rexeis *et al.*, 2005) were also included in the comparisons, although these types of model are not currently suitable for use in large-scale emission inventories.

Groups of real-world driving patterns were used as the input to the various models. The driving patterns were selected from the large TRL database (see Section 2.2.1), based upon bands of speed and positive acceleration. Each driving pattern was processed using all the models and emission factors were determined for the specified vehicle categories. The outputs from the different models were then compared, on the basis of a number of statistical parameters, with the emission factors used in the NAEI.

Generally, there was a very good agreement between the shapes of the emission curves in the NAEI and those of the various models tested. The ARTEMIS (both traffic situation and average speed) and PHEM emission factors had different shaped curves for CO and HC from petrol cars, whilst the ARTEMIS traffic situation

⁸ COPERT 4 was not available at the time this work was undertaken.

⁹ MODEM = Modelling of Emissions and Fuel Consumption in Urban Areas.

¹⁰ PHEM = Passenger car and Heavy-duty vehicle Emission Model).

curves for NO_x also differed for petrol cars. COPERT produced different shaped curves for NO_x emissions from diesel cars, HGVs and buses. VERSIT+ had different trends for CO, HC and NO_x from petrol cars, NO_x and PM from diesel cars and CO₂ from both. With regards the magnitude of the emissions estimates, the best agreements between the models appeared to be for NO_x and CO₂. For CO and HC, most of the comparisons appeared to show poor agreement, whilst for PM there was an even split between good and poor agreements.

2.3.3 Evaluation of model and emission factor accuracy

Although inter-model comparisons provide useful information on the scope of different models and differences in predictions, they cannot properly be used to assess model accuracy as this requires comparison against independent real-world datasets. Indeed, one of the most serious limitations of existing emission models is the lack of a suitable validation or calibration method. Four types of assessment were applied in an attempt to determine the accuracy of the model predictions:

- *Comparisons with on-board emission measurements.* In some studies analytical equipment has been installed in vehicles in order to measure exhaust emissions directly. Such studies have tended to focus on the regulated pollutants, and have generally been restricted to a small number of vehicles.
- *Comparisons with remote sensing measurements.* Remote sensing has been used to measure emissions from many vehicles, but only at a relatively small number of locations. Again, remote sensing studies have tended to be restricted to the regulated pollutants.
- *Comparisons with the results from the inversion of an air pollution model.* The prediction of air pollution is usually conducted using emission factors derived from laboratory emission measurements, and by applying algorithms which describe the dispersion of pollutants in the atmosphere. However, an 'inverse' modelling process can be used, in which an inverted dispersion model is applied to measured ambient concentrations in order to estimate emission factors from the traffic. Emission factors can be calculated for different vehicle categories where the characteristics of the traffic (flow, speed, composition) are known.
- *Comparisons with the results from measurements in road tunnels.* Tunnel studies have been used to determine emission factors from the traffic in a number of countries. Ambient pollutant concentrations are measured at the inlet and outlet of the tunnel, and the difference in the concentrations, when combined with information relating to the traffic, is used to derive emission factors for individual vehicle classes.

On-board measurements

For this project a single Euro 3 petrol car was fitted with a simple on-board emission analyser, driven along a set route, and the measured emissions were compared with the predicted emissions. The predicted emission of CO and NO_x were much higher than the measured values. For HC, comparable results were obtained, although MODEM predicted higher emissions than were measured. Comparable results were also obtained for CO₂, though in this case the average-speed functions in the NAEI predicted higher emissions than were measured. The results from this vehicle indicated that for emission inventories there was no obvious advantage to using more complex instantaneous models over simple speed-related emission functions. However, it should be noted this was a very limited piece of work using a single vehicle, and the measurement technique was not compared with laboratory measurement methods.

Remote sensing measurements

A small number of studies have used remote sensing to either develop or test emission models. Of most relevance to the UK was an evaluation of the COPERT III model (Ntziachristos and Samaras, 200a) using remote sensing emission measurements in Sweden (Ekström *et al.* (2004). In this study there was found to be a good agreement between the remote sensing measurements and COPERT III for petrol and diesel car NO_x emissions. For CO and HC emissions the agreement was poorer. NO_x emission factors by technology class for HDVs differed significantly between the remote sensing data and the COPERT III model, with systematically higher emission factors being obtained from remote sensing. An interesting result was that the decrease in NO_x emissions from Euro 2 to Euro 3 predicted by the COPERT III model was not reflected in the remote sensing data. The study highlighted the potential of on-road optical remote sensing for emission model evaluation

purposes. Further improvements in the measurement strategy, as well as in the data processing, could be made in order to further refine the use of remote sensing for model evaluation purposes.

Inversion of an air pollution model

For this project the air pollution prediction algorithms in the DMRB Screening Method (Highways Agency *et al.*, 2007) were inverted to estimate emission factors for vehicles on Marylebone Road, London. The calculation was conducted using air pollution data from 2004, with the roadside contribution of the traffic being determined from the difference between the concentration at the Marylebone Road and the concentration at a background site at Bloomsbury. Based on the total traffic flow, an average vehicle emission factor was also calculated. Separate emission factors (CO, NO_x and PM_{2.5}) for LDVs and HDVs were calculated using multiple regression analysis. Driving patterns recorded on Marylebone Road in 2003 were used as input to MODEM and PHEM, and the average speeds were used in the other models (apart from HBEFA, for which a traffic situation description was used).

In the case of LDVs, the DMRB inversion gave emission factors for CO, NO_x and PM_{2.5} of 7.0, 1.0 and 0.04 g vehicle⁻¹ km⁻¹ respectively. For HDVs, the emission factors for CO, NO_x and PM_{2.5} were 1.8, 7.0 and 0.25 g vehicle⁻¹ km⁻¹ respectively. However, the emission factors obtained by inversion of the DMRB were substantially higher than the predicted emission factors, although for PM the inverse model gave an emission factor which was reasonably close to the emission factor predicted using the NAEI method. It was considered unlikely that the predictions of the different emission models were systematically wrong. There are a number of errors associated with the inverse modelling approach itself, and further testing and refinement is required before this can be viewed as a reliable means of testing the accuracy of emission models

Measurements in tunnels

Air pollution measurement campaigns were conducted by TRL in the Hatfield tunnel in late 2005 and early 2006, and in the Bell Common tunnel between May 2006 and January 2007 (Boulter *et al.*, 2007). Continuous measurements were undertaken of nitric oxide (NO), nitrogen dioxide (NO₂) and ozone (O₃) at three locations within the tunnel, and the resulting data were used in conjunction with traffic data to derive emission factors for individual vehicle categories, again based upon multiple regression analysis.

One of the most significant findings of the study was the much larger emission factor for HDVs in the Bell Common tunnel (around 17 g vehicle⁻¹ km⁻¹) compared with the Hatfield tunnel (around 4-5 g vehicle⁻¹ km⁻¹) and the UK emission factors. In addition, the NO₂/NO_x proportion for such vehicles was lower in the Bell Common tunnel. These findings may have been due in part to differences in the composition of the HDV fleet and vehicle load factors, but another explanation was the difference in road gradient (0% in Hatfield, around +2% in Bell Common). However, although the gradient has an important effect, it does not fully explain the difference between the HDV emission factors in the two tunnels. It is possible that the HGVs in the Bell Common tunnel have a higher gross weight than those in the Hatfield tunnel, although no information was available to allow this to be tested.

The emission factor for cars derived from the Hatfield tunnel measurements was slightly lower than that derived from the UK emission factors. The emission factors for LGVs from the Hatfield tunnel measurements were higher than the UK emission factor.

For cars the predicted NO_x emission factors from several different models (NAEI, COPERT III, ARTEMIS, HBEFA, PHEM and MODEM) were all higher than the emission factor derived from the Hatfield tunnel data. For LGVs there was a good level of agreement between the model predictions and the measurements in the Hatfield tunnel (all gave emission factors of around 1 g vehicle⁻¹ km⁻¹).

There was much more variation in the modelled NO_x emission factors for heavy-duty vehicles. The values for rigid HGVs in the ARTEMIS average speed model and HBEFA were similar. However, the values in the NAEI were around 25% higher than those in ARTEMIS/HBEFA, and the values in COPERT III were only 50-60% of those in ARTEMIS/HBEFA. The Hatfield tunnel measurements agreed closely with the NAEI emission factors. The NAEI produced particularly high results for articulated HGVs. In this case, there was a poor agreement between the Hatfield tunnel measurements and the UK emission factors.

Overall, the results - for the rather limited set of conditions investigated - indicate that the current UK emission factors provide a reasonably accurate characterisation of NO_x emissions from light-duty vehicles, and

broadly agree with the predictions of other models used in Europe. On the other hand, the emission factors for heavy-duty vehicles are associated with a high degree of uncertainty, not least due the difficulties associated with correctly identifying vehicle types and their operation.

2.4 Effects of fuel properties on emissions

Boulter and Latham (2009b) reviewed the effects of fuel properties on emission, and the findings are summarised briefly below.

2.4.1 Fuel composition effects

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.

2.4.2 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 Directive¹¹ and the UK Renewable Transport Fuel Obligation (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. However, in the near future the biofuel content of diesel in the UK is not predicted to exceed 5% by volume.

The use of ethanol in diesel fuel can yield significant reductions in PM emissions. 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 CO₂ emissions appear not to be greatly affected. However, there appear to be few recommendations for specific adjustment factors.

¹¹ Directive 2003/30/EC.

2.5 New emission factors for use in the UK

2.5.1 Overview

The development of new emission factors was conducted in four main stages:

- (i) *Vehicle classification.* A vehicle classification structure was required so that emission test data could be assigned appropriately.
- (ii) *Data collection.* An effort was made to collect as much emission data as possible from European laboratories, with particular emphasis on the programmes conducted in the UK. The resulting data were assembled into a number of separate databases.
- (iii) *Data processing.* Prior to the development of **basic** emission factors the data were processed in a number of ways to ensure that the values were representative of UK real-world driving conditions. The data for specific vehicle categories also had to be extracted.
- (iv) *Data analysis.* Once processed, a series of calculations were undertaken to determine appropriate emission factors.

These stages were described in more detail by Boulter *et al.* (2009a), and are summarised below. The term 'basic' is used above to indicate that the emission factors are either normalised or reflect current vehicle and fuel technologies, and should be used in conjunction with scaling factors when estimating actual emissions. The development of appropriate scaling factors is described later in this Chapter. The scaling factors cover aspects such as the actual mileage of vehicles in different categories and years, the effects of changes to fuels, and the effects of specific emission-control technologies.

2.5.2 Vehicle classification

In emission inventories and air pollution models traffic data are required for a large number of vehicle categories in order to reflect variation in emission behaviour. The classification of a vehicle during testing has a crucial bearing on how the resulting emission data can be used in models. Systems of traffic classification vary, but they generally reflect the typical formats of available traffic data and/or emission-related criteria (*e.g.* Euro standards).

Some of the vehicle categories currently used within the NAEI are very broad. For example, HGVs are simply sub-divided by 'rigid' and 'articulated'. The emissions from a 12-tonne, 2-axle rigid truck are likely to be very different from a 34-tonne, 4-axle rigid tipper. However, the recent increase in the amount of available emission data has allowed a more detailed structure to be proposed for use in the UK, and this is shown in Figure 1.

In Figure 1 the sub-division of the traffic is shown in terms of 'levels'. In both cases the traffic is divided into three main categories: LDVs, HDVs and two-wheel vehicles. For each of these main categories, a further sub-division is required according to a number of criteria, including fuel type (*e.g.* petrol, diesel, LPG), engine size or weight, and compliance with emission control legislation. Not all the details are included below Level 3. Activity data for Levels 0-2 is usually available from traffic counts and models. The disaggregation of the traffic at Levels 3-6 is usually undertaken by emission and air pollution modellers.

The main enhancements in the 2009 update to the existing emission factors include the following:

- The addition of fuels other than petrol and diesel for LDVs.
- The addition of Euro 5 and Euro 6 LDVs.
- The inclusion of taxis (black cabs) as a separate category.
- The sub-division of rigid HGVs, articulated HGVs, buses and coaches by weight band.
- The addition of Euro V and Euro VI HDVs.
- The sub-division of two-wheel vehicles into mopeds and motorcycles.
- The sub-division of motorcycles by engine size band.

These aspects have been addressed in the basic emission factors. Further enhancements are included in the scaling factors (*i.e.* they are addressed via adjustments to the basic emission factors).

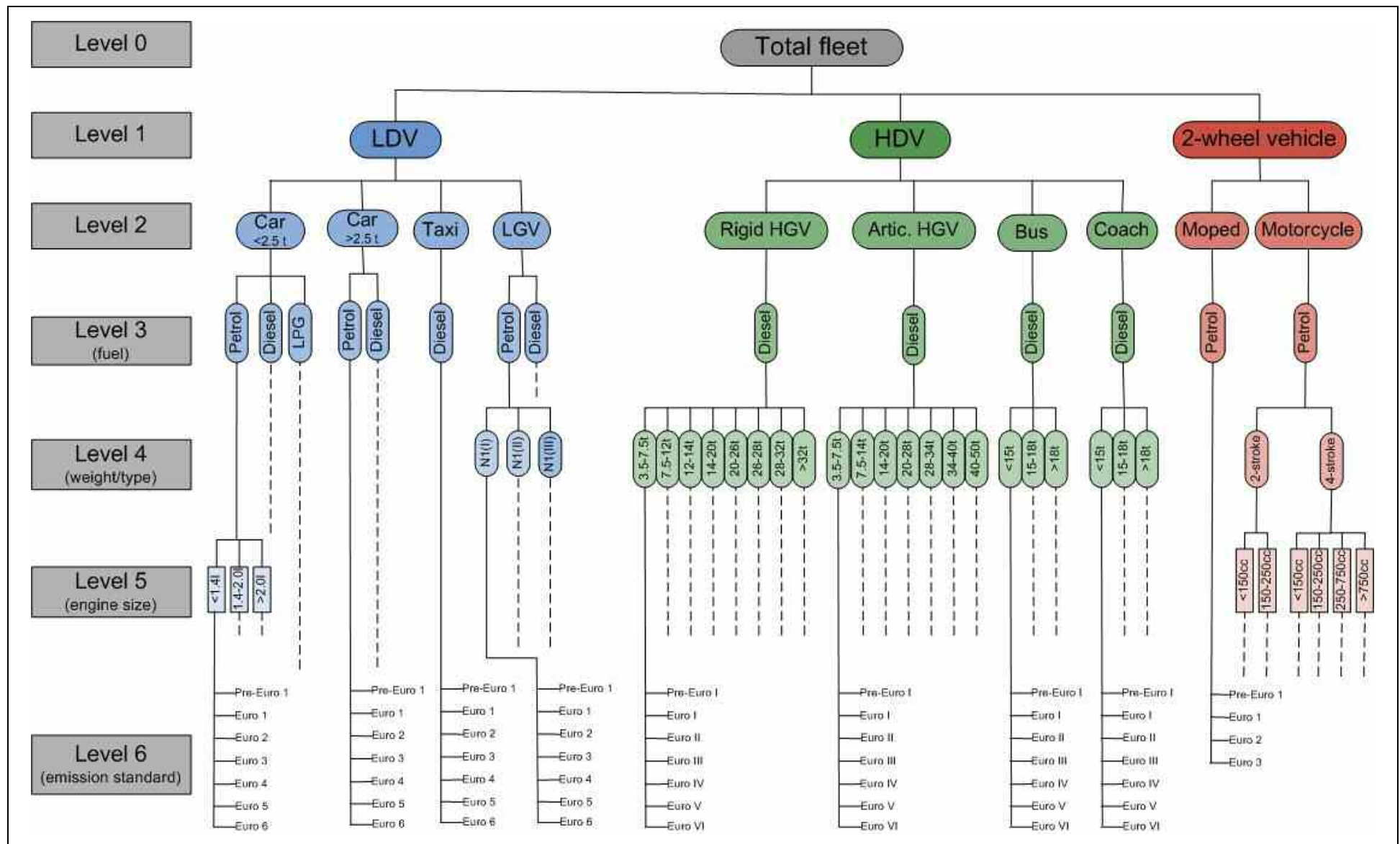


Figure 1: Structure of the road vehicle fleet (basic 2009 emission factors).

2.5.3 Data collection

Emission data for LDVs and HDVs from 29 European test programmes were used in the project. The starting point for data collection was the database compiled in the Emission Factors 2000 project (Barlow *et al.*, 2001). As far as possible, bag measurements were used, although for some unregulated pollutants aggregated continuous measurements were included. In the case of the regulated pollutants and CO₂, standard measurement techniques were employed throughout. On the other hand, the various unregulated pollutants were measured using a range of different techniques, such as gas chromatography/mass spectrometry (GC/MS), Fourier-transform infrared spectroscopy (FTIR) and, for particle size measurement, a micro-orifice uniform deposit impactor (MOUDI).

Four separate databases were compiled:

- (i) Light-duty vehicles – regulated pollutants (including CO₂).
- (ii) Heavy-duty vehicles – regulated pollutants (including CO₂).
- (iii) Light-duty vehicles – unregulated pollutants.
- (iv) Heavy-duty vehicles – unregulated pollutants.

For each of the four databases, the basic structure was taken from the Light Vehicle Emission Measurement database compiled in ARTEMIS (André, 2005; Kljun *et al.*, 2005; Joumard *et al.*, 2006b). This structure is based upon three main groups of parameters, with each group being divided into a number of sub-categories:

- (i) *Vehicle parameters*. These parameters provided information on each tested vehicle, such as the make, model, year of registration, engine size, fuel type and emission legislation. Each vehicle had its own unique identification code.
- (ii) *Test parameters*. These parameters described the conditions under which the test was conducted, and any other relevant information relating to the test, such as the date, the laboratory, the driving cycle, the ambient temperature, *etc.*
- (iii) *Pollutants*. These parameters described the emission factors and fuel consumption associated with each test.

The full LDV-regulated database contained data for more than 48,000 tests on almost 3,400 vehicles. Most of the vehicles tested (around 95%) were cars less than 2.5 tonnes in weight, and around 85% of these had a petrol engine. There was also a strong bias towards older vehicles, with more than 80% of the vehicles tested conforming with pre-Euro 1 or Euro 1 emission standards. Only 38 vehicles (1%) complied with Euro IV emission standards. The full HDV-regulated database was much smaller than the LDV-regulated database, containing 1,454 tests on 125 vehicles. Almost all the tests were conducted on vehicles running on conventional (fossil) diesel. The LDV-unregulated database contained tests on 276 vehicles.

In the case of two-wheel vehicles much of the data from UK tests was already included in the extensive database of the ARTEMIS project (Elst *et al.*, 2006), and therefore the compilation of a separate database was considered to be unnecessary. The ARTEMIS emission functions for two-wheel vehicles are therefore presented here (with some slight modifications, as requested by DfT), for use in the UK.

2.5.4 Data processing

LDV-regulated database

Adjustment factors were used to normalise the raw LDV data. This allowed all data to be included (*e.g.* low-temperature tests), and rendered the database internally consistent. During the application of the emission factors, scaling factors are required to allow actual conditions to be taken into account. The LDV-regulated database was normalised as follows:

- (i) The test results (CO, HC, NO_x, PM, CO₂) were firstly normalised to a temperature of 10°C (UK annual mean). The normalisation was undertaken using functions provided by Laurikko (2005).
- (ii) The test results were then normalised to an accumulated vehicle mileage of 50,000 km. The mileage adjustment factors (cars only, CO, HC and NO_x) were derived from the database itself. Too few PM measurements were available to obtain deterioration functions. The literature suggests that CO₂

emissions are not affected by vehicle mileage (Samaras and Ntziachristos, 1998; Ntziachristos and Samaras, 2000b; Samaras and Geivanidis, 2005), and hence the CO₂ measurements were not adjusted.

The LDV-regulated database was then reduced in size by the exclusion of certain types of test. The tests which were excluded were:

- (i) Tests conducted over the driving cycles used in European vehicle type approval (ECE, EUDC, NEDC). These cycles were considered to be unrepresentative of real-world driving conditions. The reduced database therefore only contained emission factors obtained over 'real-world' driving cycles.
- (ii) Tests with a cold or warm start. The reduced database only contained hot-start emission factors.

After normalisation and reduction the LDV-regulated database contained 1,466 vehicles and 28,312 tests. For each combination of vehicle type, fuel type, emission standard and pollutant the sub-set of speed and emissions data was extracted from the main database. No distinction was made between vehicles equipped with manual or automatic transmission; it was assumed that the distribution of transmission types in the sample was representative of that in the vehicle population. The number of data points in a sub-set varied greatly.

HDV-regulated database

Based on extensive data on pre-Euro I to Euro III vehicles from the Dutch and German in-use compliance programmes, Rexeis *et al.* (2005) found that that no mileage corrections to the emission factors were required for any Euro class. No processing of the HDV-regulated database was therefore undertaken.

LDV-unregulated database

In the case of the LDV-unregulated database, the only step taken was to remove tests with cold or warm starts. Such tests accounted for 18% of the full database. Tests over type approval cycles were retained, as their exclusion would have resulted in the depletion of a database which was already rather limited in size. No normalisation was conducted for ambient temperature, mileage or any other parameter due to a lack of relevant supporting data.

HDV-unregulated database

The HDV-unregulated database was treated in a similar manner to the LDV-unregulated database, with the results from warm-start tests and cold-start tests being removed prior to analysis, although such tests were relatively few in number. Again, no normalisation was conducted for ambient temperature, mileage or any other parameter due to a lack of relevant supporting data.

2.5.5 Data analysis

Regulated pollutants (CO, HC, NO_x, PM)

Light-duty vehicles

For each combination of vehicle type, fuel type, emission standard and pollutant, a regression curve was fitted to the emission data (in g/h) and average trip speed data. The advantages of using the g/h data rather than the g/km data were that simpler regression functions could be used and that the regression fits resulted in more appropriate gradients at low speeds. For example, as the trip speed approaches zero the emission factor, when stated in g/km, approaches infinity. On the other hand, the emission rate (in g/h) has a finite value at zero speed. If reliable emissions data at idle (*i.e.* zero speed) were also available, it would also be possible to fix the zero end of the curve, potentially giving more reliable emissions at very low speed. However, the existing test programmes did not include an idle test (where mass emissions were measured), so the curves had to be fitted to the existing data.

For each set of data, one of 17 different regression models was applied. The best model was selected based on a number of considerations, including the r^2 value. The resulting functions were converted to give emission factors in g/km by division throughout by the speed term (x). The selected functions (both per unit time and per unit distance) were then plotted against the data, and the results were checked by eye. Where the model fit

was obviously incorrect (*e.g.* it gave negative or extremely high emission values), a more appropriate model was selected. In some cases a constant term was used.

Heavy-duty vehicles

The derivation of emission factors for regulated pollutants directly from the corresponding database would have led to substantial gaps. For greater flexibility, the average-speed emission factors from the ARTEMIS project were taken as the basis for the UK emission factors.

Boulter and Barlow (2005) described the derivation of a large number of average-speed fuel consumption and emission functions for conventional heavy-duty road vehicles in ARTEMIS. The functions were based on the database of fuel consumption values and emission factors. The exhaust pollutants covered were CO, THC, NO_x and PM.

The three main heavy-duty vehicle categories defined in the model are 'coaches', 'urban buses' and 'heavy goods vehicles'. These are then further divided into sub-groups according to type and mass. At the most detailed level in the ARTEMIS model the sub-groups are divided into emission legislation classes. Three levels of vehicle load are taken into consideration: 0%, 50% and 100%, and seven gradient classes are included: -6%, -4%, -2%, 0%, +2+, +4% and +6%. The emission factors for other gradients and loads can be used where suitable input data are available, and if the user of the emission functions wishes to calculate emissions for a specific vehicle load or gradient, the values can be interpolated. For the UK emission factors, a gradient of 0% was used. The vehicle load values for HGVs, buses and coaches were 56%, 50% and 50% respectively.

The database of emission factors which was compiled in this project was not used to derive any functions directly, but it was used to provide adjustments to the ARTEMIS model predictions where appropriate. In most cases the ARTEMIS predictions matched the UK data at a level which was taken to be acceptable. However, in a number of cases the match was poorer. In such cases, a single adjustment factor was used to scale the ARTEMIS prediction to give an approximate match to the UK data.

Many of the ARTEMIS emission functions for heavy-duty vehicles exhibited a reduction in emissions for any increase in speed. This contradicts the accepted view that emissions should increase at very high speeds as a result of greater air resistance. This may be due to insufficient high-speed emission tests. Consequently, the emission factor curves for heavy-duty vehicles were modified. For all HGVs, buses and coaches, the emissions were evaluated from the functions at speeds from 5 km/h to 90 km/h. The resulting emissions were inspected after the 60 km/h value. Where values were found to be decreasing, the g/km values were modified. For HGVs, the values were modified so as to increase slightly at higher speeds, whereas for buses and coaches, the values were modified to level out at higher speeds.

Two-wheel vehicles

The emission factors for mopeds were taken from COPERT 4. Average-speed emission factors for motorcycles (CO, HC, NO_x) were taken from ARTEMIS (Elst *et al.*, 2006).

Carbon dioxide

Cars

For most categories of petrol and diesel car the CO₂ emission functions derived from the LDV-regulated database showed little or no difference between all Euro categories. Although CO₂ emissions are not explicitly regulated at vehicle type approval, they are measured to enable fuel consumption to be calculated. Consequently, a large amount of CO₂ data exists. However, in contrast to the database, the type approval data for new cars, and publications by the European Commission and car manufacturers, indicate that new car CO₂ emissions are decreasing with time (European Commission, 2007). Consequently, an alternative approach to generating CO₂ emission functions was used which took into account the reduction in emissions from new cars, based on the type approval test.

The principal reason for basing the CO₂ functions primarily on the type approval data was that the sample size was much larger than that in the database of measurements over real-world driving cycles. Whilst at one level this is clearly not consistent with the approach used for other pollutants, whereby type approval data are

rejected, it could be argued with some justification that CO₂ is less susceptible to differences between real-world cycles and the NEDC than other pollutants. The approach is described by Boulter *et al.* (2009b).

It should be noted that the CO₂ data which form the basis of these calculations do not fully reflect real-world vehicle operation. For example, real-world CO₂ emissions are affected by a number of factors, including the use of auxiliaries (headlights, radios, air conditioning, *etc.*), the prevalence of 'eco-driving' and level of maintenance. In fact, for cars a combined 'uplift' factor of +15% on NEDC-based CO₂ emission factors has been agreed between DfT and DEFRA to take into account the various real-world effects (DEFRA, 2007). Otherwise, models are available to allow factors such as air conditioning to be taken into account (*e.g.* Roujol, 2005).

The analysis described in the previous section relates to the tailpipe emissions. In order to derive the ultimate CO₂ emissions, emissions of all other pollutants which are subsequently oxidised to CO₂ in the atmosphere also need to be taken into consideration, and the resulting additional CO₂ added to the tailpipe values. For modern petrol and diesel cars the effect is very small – an increase of 1% or less. However, for pre-Euro 1 petrol cars, which produce higher quantities of CO and HC, the effect is greater. Again, the approach is described by Boulter *et al.* (2009b).

The CO₂ emission factors for N1(III) LGVs were used to represent emissions from taxis.

LGVs

Only a limited amount of emissions data was available for LGVs, and therefore various assumptions had to be made. Small LGVs (N1, class I) are mainly car-based vans. For this category, the CO₂ emission factors were taken from the equivalent medium-sized cars. A small adjustment was added to the function to allow for the higher vehicle weight of an in-use van. For larger vans, data were available for some Euro classes but not all. Curves were generated based on the existing data. The emission factors for the remaining categories were based on the known functions, modified by assumptions on the likely change in emissions between Euro classes.

HDVs

For heavy-duty vehicles, the CO₂ functions were based on those from the ARTEMIS project (Boulter and Barlow, 2005).

Two-wheel vehicles

The CO₂ emission factors for mopeds were taken from COPERT 4. As for regulated pollutants, the CO₂ emission factors (ultimate CO₂) for motorcycles were taken from ARTEMIS (Elst *et al.*, 2006).

Unregulated pollutants

The unregulated pollutants considered were methane (CH₄), 1,3-butadiene, benzene, nitrous oxide (N₂O), ammonia (NH₃), polycyclic aromatic hydrocarbons (PAHs), NO₂ and PM size fractions. Emission factors were calculated according to the availability of data. If sufficient measurements were available across the whole speed range, average-speed functions were developed. If sufficient measurements were available for specific driving cycles, then emission factors for urban, rural and motorway conditions were calculated. In the case of PAHs, single emission factors were used for all driving conditions. As far as possible, the emission factors were derived from the LDV-unregulated and HDV-unregulated databases. Where little or no information existed, the emission factors from COPERT 4 were used, or assumptions were made based on the type approval limit values for total hydrocarbons.

The proportions of NO_x emitted as primary NO₂ were taken from COPERT 4. For the UK it is recommended that modellers use these values unless they have access to more appropriate information. In addition, some further assumptions will be required for the vehicle categories which are not covered (*e.g.* for two-wheel vehicles, Euro 5/6 light-duty vehicles, light-duty vehicles and Euro IV heavy-duty vehicles equipped with catalysed DPFs).

To calculate emissions of PM₁₀ and PM_{2.5} it is recommended that the baseline functions for total PM mass should be used. In other words, it is assumed that all exhaust PM is PM_{2.5}. This is in line with the

recommendation from COPERT 4, given that there is no physical process occurring in an engine that could produce primary particles as large as 2.5 µm. Any coarse particles measured in tests probably result from the sampling system walls and not primary engine exhaust (Ntziachristos, 2008). No emission factors are available for PM₁.

Simplification of the emission functions

During the average-speed curve fitting process, a variety of different functions were used in order to produce the best possible fit and the best curve shape. This resulted in a large number of different types of functions. The final step in the process was to fit a 6th-order polynomial to the values calculated using each regression curve. This enabled the speed-emission curves for most vehicle categories to be calculated using the same basic functional form.

2.5.6 Basic emission factors

The basic emission factors were given by Boulter *et al.* (2009b), and are not repeated here. They are available in the spreadsheet *Road vehicle emission factors 2009 - regulated (Final 14-May-09).xls*.

2.6 New emission scaling factors

The basic emission factors were complemented by scaling factors to take account of (i) mileage effects associated with vehicle samples and (ii) future improvements in fuels and vehicle technologies (Boulter, 2009; Boulter and Latham, 2009). The need for scaling factors for biofuels was also considered.

Vehicle mileage scaling factors

An emission factor for a particular vehicle type and emission standard is usually an average value for vehicles of different ages and mileages which inherently takes account of possible changes in emissions with vehicle age, relative to new vehicle emissions performance. However, vehicles which are now rather old would have been relatively new when tested, with a relatively low mileage. For example, the accumulated mileage of Euro 2 vehicles would generally be very different in 1998 and 2005. Therefore, it is possible to refine the basic emission factors using scaling factors for the deterioration in emissions with age or mileage. This is not an altogether straightforward process, as different scaling factors are required for different years, and information is required on the average accumulated mileage of different types of vehicle by year.

Cars and light good vehicles

Rather than using existing mileage scaling factors, new scaling factors for cars and LGVs were determined from the database of emission measurements compiled within the project. The following steps were taken to adjust the measured emission factors to take account of the wide range of vehicle mileage during tests:

- (i) To generate the basic emission functions for cars, the emission test data were normalised to an accumulated mileage of 50,000 km for each vehicle type and pollutant. This process was described by Boulter *et al.* (2009b). Only the emission factors for CO, HC and NO_x were normalised for mileage. Too few PM measurements were available to obtain deterioration functions, and literature suggests that CO₂ emissions are not affected by vehicle mileage.
- (ii) For each vehicle category, the average age was calculated for the range of reference years of interest (1995-2030).
- (iii) Relationships between vehicle age and mileage were established, and the average mileage was then calculated for each vehicle category and reference year.
- (iv) For each vehicle category, reference year and pollutant, the emission factor associated with the actual average mileage and the emission factor for 50,000 km were calculated. The scaling factors were calculated by dividing the emission factor for the actual mileage by the emission factor for 50,000 km.

Some examples of values of the mileage scaling factors are presented by Boulter (2009). However, these are not definitive. Users of the emission factors must calculate their own mileage scaling factors based on appropriate vehicle age and mileage distributions for each vehicle category and year.

Heavy-duty vehicles

The general conclusion from the ARTEMIS work on HDVs was that no emission deterioration factors were needed for Euro I to Euro III vehicles. It was also concluded that there is no reason to assume that the deterioration pattern of engine-out emissions from Euro IV and Euro V vehicles would differ much from engines of earlier Euro classes. However, the ageing, malfunctioning and tampering of emission-control devices on Euro V and later vehicles could lead to increased emissions. At present, it is not possible to give exact values since the technology is not fully developed and few data are available (Rexeis *et al.*, 2005).

The database of heavy-duty emission factors compiled in this project was considered to be too small to allow deterioration effects to be examined. As a consequence of this, and taking into account the findings of ARTEMIS, no mileage scaling factors were developed for heavy-duty vehicles.

Two-wheel vehicles

For the UK, Boulter *et al.* (2009b) recommended the use ARTEMIS emission factors for two-wheel vehicles. However, emission degradation was not studied in ARTEMIS and no degradation functions were available. This was identified as an area for further research (Elst *et al.*, 2006).

Fuel composition scaling factors

The scaling factors for fuel composition (sulphur content) were derived by Boulter and Latham (2009b). In order to derive fuel composition scaling factors, an adapted version of the method presented in COPERT III (and retained in COPERT 4) was used. The baseline fuels which were used were identical to those used in COPERT, except for the addition of 'Fuel 2009' having a maximum sulphur content of 10 ppm. The correspondence between fuels and emission standards, for all vehicle types, was also taken from COPERT, with the addition of a 2009 fuel. It was assumed that there would be 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 scaling factors were determined for two-wheel vehicles.

Scaling factors for biofuels

Based upon the available evidence, Boulter and Latham (2009b) concluded 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.

Technology scaling factors

For future LDV technologies, such as Euro 5 and Euro 6 cars, assumptions were made to derive the basic emission factors, based upon the limit values in legislation (Boulter *et al.*, 2009b). No further assumptions are required, as technological improvements are accounted for implicitly. For example, for LDVs the use of a DPF will be required to meet the Euro 5 and Euro 6 PM standards and this is taken into account in the basic emission factors. However, an important consideration is the fitting (or retro-fitting) of a DPF to pre-Euro 5 diesel vehicles. Where this is the case, it is assumed that the basic PM emission factor is multiplied by 0.1 (*i.e.* the DPF leads to a 90% reduction in PM mass emissions).

For heavy-duty vehicles, the majority of Euro VI vehicles are expected to be fitted with DPFs, whereas Euro V vehicles are not expected to need them to meet the limits. Again, this is taken into account in the basic emission factors for Euro V and Euro VI vehicles. For pre-Euro V heavy-duty vehicles retro-fitted with a DPF, a scaling factor of 0.1 is again recommended.

2.7 HGV and bus classification

The heavy-duty vehicle emission factors (HGVs, buses and coaches) are given by gross vehicle weight (GVW) categories. The GVW characterisation can generally be derived from vehicle licensing statistics. However, classified traffic count data will only classify vehicles by their number of axles. The corresponding axle configurations are shown in Table 4 (note this is approximate).

Table 4: HGV weight classification and corresponding axle configuration.

Vehicle type	Sub category	Axles
Rigid truck	< 7.5 t	
	7.5 to 12 t	2-Axle
	12 to 14 t	
	14 to 20 t	3-Axle
	20 to 26 t	
	26 to 28 t	4-Axle
28 to 32 t		
> 32 t		
Artic/trailer truck	< 28 t	3+4 Axle
	28 to 34 t	
	34 to 40 t	5 Axle 6+Axle

Buses and coaches are similarly classified by their weight in the emission factors. An explanation of the sub-categories is shown in Table 5.

Table 5: Bus weight classification and description.

Vehicle type	Sub category	Explanation
Bus	<15 t	Single deck midi bus. Length up to 12 m long. Up to 40 seats.
Bus	15-18 t	Single deck bus. Length 12 m or longer. Over 40 seats. All double deck buses. Over 40 seats.
Bus	>18 t	Articulated buses (bendy buses)
Coach	15-18 t	2 axle coach
Coach	>18 t	3 axle coach

3 Cold-start emissions

3.1 Background

If a vehicle has not been used for several hours, the temperatures of its engine and exhaust system will normally be similar to that of the ambient air. Once the engine is started and a journey begins, the temperatures of the engine and exhaust system gradually increase until they become comparatively stable at their normal operational levels. Rates of emission and fuel consumption are higher during the warm-up phase than during thermally stable operation, particularly in the case of petrol-engined vehicles. There are a number of reasons for this, including incomplete combustion, catalyst inefficiency, increased viscous friction due to the low lubricant temperatures in the engine and transmission, and increased rolling friction in the tyres. The emissions produced during the warm-up phase are often called ‘cold-start’ emissions¹².

3.2 Definitions of cold-start emissions

Figure 2 shows an idealised representation of the instantaneous emission rate of a given pollutant as a function of time following an engine start ($t=0$). Under real-world driving conditions, the emission profile is much more variable than the one shown. The emission units and time units in this example are arbitrary, as the actual values are dependent upon multiple factors. The emission profile can be divided into an initial transient phase - during which the emission rate is initially high but decreases as the temperatures of the engine and catalyst increase - followed by a stable phase when the normal operational temperatures have been reached. The duration of the first (cold-start) phase is signified by t_{cold} , and the emission rate during thermally stable operation is given by E_{hot} . Area A represents the total hot emission during the cold-start period ($E_{hot} \times t$), and area B represents the total cold-start excess emission during the same period. The total emission during the cold-start period is therefore given by $A+B$.

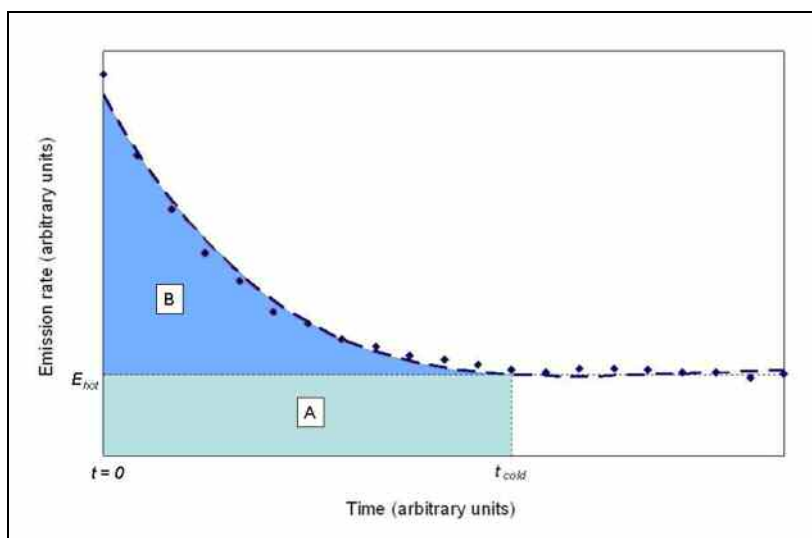


Figure 2: Schematic representation of emission rate as a function of time following an engine start (adapted from André and Joumard (2005)).

There are a number of different ways of presenting cold-start emission results. These include the following:

- (i) The absolute total emission (in grammes) for the cold-start period (*i.e.* $A+B$).
- (ii) The absolute excess emission (in grammes) for the cold-start period (*i.e.* B).

¹² Wherever a general reference is made in this Report to ‘cold-start emissions’, this can be taken to mean ‘cold-start emissions and fuel consumption’, unless otherwise stated.

(iii) The quotient of cold and hot emissions (B/A).

Clearly, in all three cases the cold-start period (*i.e.* the value of t_{cold}) needs to be clearly defined.

The methodology used to determine cold-start emissions has a major influence on the results (Weilenmann *et al.*, 2005). Cold-start emission factors have traditionally been determined via the collection of bag samples of the exhaust gas from vehicles operated on a chassis dynamometer from hot and cold starts under otherwise identical test conditions (including the same driving cycle)¹³. Most commonly, either the hot-start emissions have then been subtracted from the cold-start emissions to give an ‘absolute excess’ cold-start emission in grammes (equivalent to B in Figure 2), or a ‘relative’ cold-start emission factor over the full distance of the cycle (B/A) has been calculated. These terms are used in this Review, and where the text refers to cold-start emissions, the terms ‘absolute excess’ and ‘relative’ are used in this context, unless otherwise stated. In the case of the relative cold-start emission, if the driving cycle length does not exactly match the cold-start distance, then the quotient will be either underestimated or overestimated. It is likely that this will occur for almost all tests, and therefore the absolute cold-start emission value ought to be used where possible.

As an alternative, a short sub-cycle can be repeated several times. The overall duration of the driving cycle must be such that at least the last two sub-cycles are driven with a hot stabilised engine. The cold-start extra emissions can then be derived from the difference between the emissions measured during the sub-cycles when the engine is warming up, and the emissions measured over the same number of sub-cycles when the engine is hot (Weilenmann, 2001; Weilenmann *et al.*, 2005). According to Weilenmann *et al.* (2005), any test to generate cold-start emission factors ought to be based on repeated ‘real-world’ driving cycles (*i.e.* the driving cycles are derived from studies of real-world traffic and are statistically representative). However, some cycles (such as the FTP-75 and ECE legislative cycles) are not fully repetitive in this sense, and therefore a regression modelling approach has been applied to estimate cold-start emissions (*e.g.* Heeb *et al.* 2001; Weilenmann, 2001). Figure 3 shows cumulative CO emissions (solid line) during a driving cycle (dashed line). The thermally stable phase is approximated by the straight line. The intercept of this line on the x -axis gives the cold-start emission. Using this methodology it is possible to calculate cold-start emissions using measurements over non-repetitive cycles. In particular, the FTP-75 and ECE legislative cycles, for which a large number of measurements exist, can be used (Weilenmann, 2001).

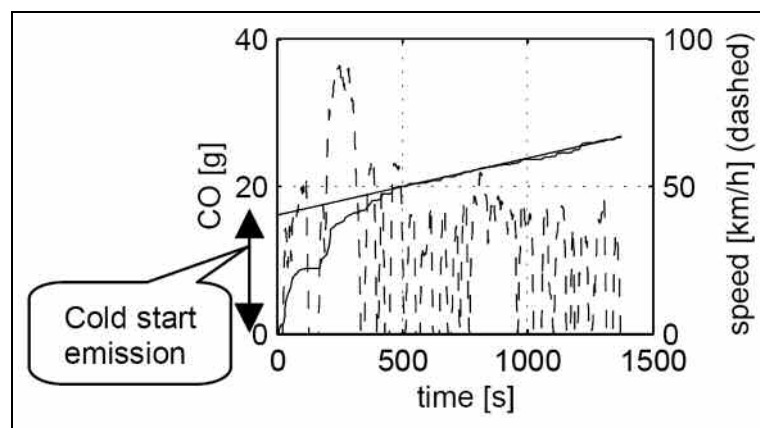


Figure 3: Cumulative CO emissions over a driving cycle, and definition of cold-start emission (Weilenmann, 2001).

3.3 Factors affecting cold-start emissions

A wide range of factors affect cold-start emissions, including the following:

- The pollutant.
- The vehicle type (*e.g.* car, light commercial vehicle, heavy goods vehicle).
- The fuel type (*e.g.* petrol, diesel).

¹³ It has not always been fully clear whether the test to determine the hot emission factor has, itself, involved an engine start.

- The level of vehicle technology, which is generally stated in terms of compliance with emission legislation (e.g. pre-Euro I, Euro I, Euro II, *etc.*), and the engine management strategy.
- The engine and catalyst temperatures at the start and end of each journey. Not all journeys begin with the engine and catalyst at the ambient temperature and end with them at their full operational temperatures. The engine and catalyst temperatures - and/or their rates of change - are dependent on factors such as:
 - The ambient temperature
 - The wind speed
 - The parking duration
 - The driving cycle during the cold-start period.

The need to take into account all these factors, and the general absence of relevant data, means that accurate cold-start modelling is rather difficult.

3.4 Cold start emission models

Several examples of cold-start emission models were described by Boulter and Latham (2009a), and these are summarised below. It was not possible to conduct direct quantitative comparisons between the different models, as the sensitivity of models to certain parameters (such as driving cycle, temperature), combined with differences in modelling approaches input data requirements, mean that such comparisons are not meaningful. There is also no independent means of verifying the accuracy of model estimates, and therefore the suitability of models for the NAEI was judged in relation to how up-to-date and comprehensive they were.

COPERT

The COPERT¹⁴ methodology is one of the most widely used in Europe for estimating emissions at the national level, and it is the preferred method in the European Environment Agency's Emission Inventory Guidebook (EEA, 2007). For cold-start emissions, COPERT also forms the basis of the NAEI.

In December 2008 a revision to the road transport Chapter of the EMEP/CORINAIR Emission Inventory Guidebook was produced. It was also proposed that this method would be used in COPERT 4, but it did not include an updated cold-start emission calculation approach. At the time of writing, the compilers of COPERT were working on a new cold-start calculation methodology for the COPERT 4 software which includes more detailed calculations for late-technology vehicles.

MEET

The MEET project provided a basic Europe-wide procedure for evaluating the impact of transport on air pollutant emissions and energy consumption (European Commission, 1999). MEET incorporated a slightly different cold-start routine to COPERT II (COPERT III is a hybrid of COPERT II and MEET). The method was developed empirically using data assembled from many European test programmes. Sufficient data were only available for cars, for which a distinction could be made between diesel and petrol vehicles with and without a catalyst, but there were too few data from catalyst-equipped diesel vehicles to allow a detailed analysis to be undertaken.

EXEMPT

A model called EXEMPT (EXcess Emissions Planning Tool) was developed by AEA Technology as part of the DfT TRAMAQ programme (Blaikley *et al.*, 2001). The model takes the form of an Excel spreadsheet, and is designed to predict the effects of different parking control scenarios on excess cold-start emissions.

The model is run in three stages:

- (i) The initial driving stage. The user defines ambient and engine start temperatures and the distance driven.
- (ii) The parking stage. The user defines the ambient temperature and parking time start engine temperature can be specified or calculated from stage (i).

¹⁴ <http://lat.eng.auth.gr/copert/>

- (iii) A further driving stage. The user defines ambient temperature and driving distance start engine temperature can be specified or calculated from stage (ii).

The model also allows the user to define the percentage of the vehicle fleet made up of each vehicle category for which experimental data has been collected. The user specifies the total number of vehicles and the conditions for which the model is to be run. The total excess emission of each pollutant is then calculated using these data.

Blaikley *et al.* (2001) state that the application of the model is limited by the scope of the data upon which it is constructed (*i.e.* a relatively small sample of passenger car models). This has the effect of limiting the accuracy of its current predictions, the range of potential applications and the lifetime of its serviceability. These are not limitations of the model itself but of the emissions data embedded within it. These limitations could therefore be overcome by subsequent incorporation of additional emissions data from, for example, other vehicle classes such as PSVs or HGVs, or, at a later date, more modern technology vehicles as they achieve significant penetration of the national vehicle fleet. However, one of the main limitations of this model is the lack of readily available input data on vehicle thermal condition and parking durations which are relevant to the UK. However, if this can be found, or obtained via a separate study this could provide valuable data for modifying the NAEI cold-start factors. No applications of the model appear to have been reported in the literature.

HBEFA

The Handbook of Emission Factors (HBEFA) is a road transport emission model which is used for both national inventories and local applications in Germany, Austria and Switzerland. The model is based on reference emission factors for different categories of vehicle. Each emission factor is associated with a particular traffic situation, characterised by the features of the section of road concerned (*e.g.* 'motorway with 120 km h⁻¹ limit', 'main road outside built-up area'). The user cannot specify detailed driving conditions such as driving patterns and actual speeds. Instead, the scenarios built into the model are accessed via a series of selection criteria. The variability of traffic speed for a given traffic situation is defined via a textual description (*e.g.* 'free-flow', 'stop-and-go') (INFRAS, 2004). The emission factors produced by the Handbook for the various vehicle categories must then be weighted according to traffic flow and composition.

In the HBEFA an additional emission is introduced for each start event to allow for the cold-start effect. The user can define the ambient temperature, journey length, soak time, and driving pattern (which determines the proportion of vehicles operating in cold-start mode).

A revised cold-start model for the Handbook of Emission Factors is planned for 2009.

COLDSTART

In Sweden VTI has developed a detailed model called COLDSTART which describes cold-start emissions as a function of ambient temperature, wind velocity, vehicle technology level (including the use of engine heating), parking location, and parking duration (Hammarström and Edwards, 1997). The model includes engine warm-up and cool-down profiles. Although these attributes indicate that the COLDSTART model should be considered for assessments on a small spatial scale, the level of input data required render it unsuitable for national-scale emission modelling.

ARTEMIS

The ARTEMIS project included the development of a new cold-start emission model. André and Joumard (2005) built upon the experience gained during MEET, and collated emissions data from a wide variety of European laboratories. The data included details of the test vehicles (fuel type, model year and engine capacity), driving cycle, ambient temperature, vehicle starting temperature, and the emission measurements under these conditions.

Three models were produced from the analysis of the data, taking into account the average speed, ambient temperature and distance travelled, amongst other parameters. The models are based on measurements over four driving cycles covering average speeds between 18.7 km h⁻¹ to 41.5 km h⁻¹ and starting temperatures between -20°C to 28°C. The models are:

- Model 1: excess cold-start emission per start.
- Model 2: excess cold-start emission from traffic.
- Model 3: aggregated cold-start emission factors.

In the first model the cold-start excess emission (per vehicle) is expressed in grammes per start for each pollutant and vehicle category (petrol and diesel cars, from pre-Euro 1 to Euro 4). This can be adjusted depending upon on average speed, ambient temperature, travelled distance and parking duration. The second model was developed to assess the excess emissions of a traffic stream using many driving behaviour statistics, and is therefore very complex. It allows the user to modify default data in order to model very specific situations. The third model was derived by running the second one, and provides European-average excess emission factors (in g/km) for a specified hour, based upon the vehicle category and pollutant, the average speed, the ambient temperature, the hour in the day (which gives the parking time distribution) and the season(which gives the trip length distribution).

In order to illustrate the relative effects of the different parameters, some examples are given for CO in Figure 4 for the influence of average speed and vehicle type, Figure 5 for the influence of ambient temperature and average speed, Figure 6 for the season influence, and Figure 7 for the influence of the hour. The influence of all these parameters depends on the pollutant considered. Nevertheless, the ambient temperature, the average speed and the hour in the day are generally the most important factors. The season, for a given ambient temperature, plays a minor role.

The three models can be used for numerous vehicle technologies (fuel and emission standard) covering the European situation, and for regulated as well as unregulated pollutants. The models can be applied at different geographic scales: at a macroscopic scale (national inventories) using road traffic indicators and temperature statistics, or at a microscopic scale for a vehicle and a trip. The complex model is time-consuming to run and the input data are available to few model users. For specific locations INRETS are able to run the complex model for the local condition, assuming the relevant input data are available.

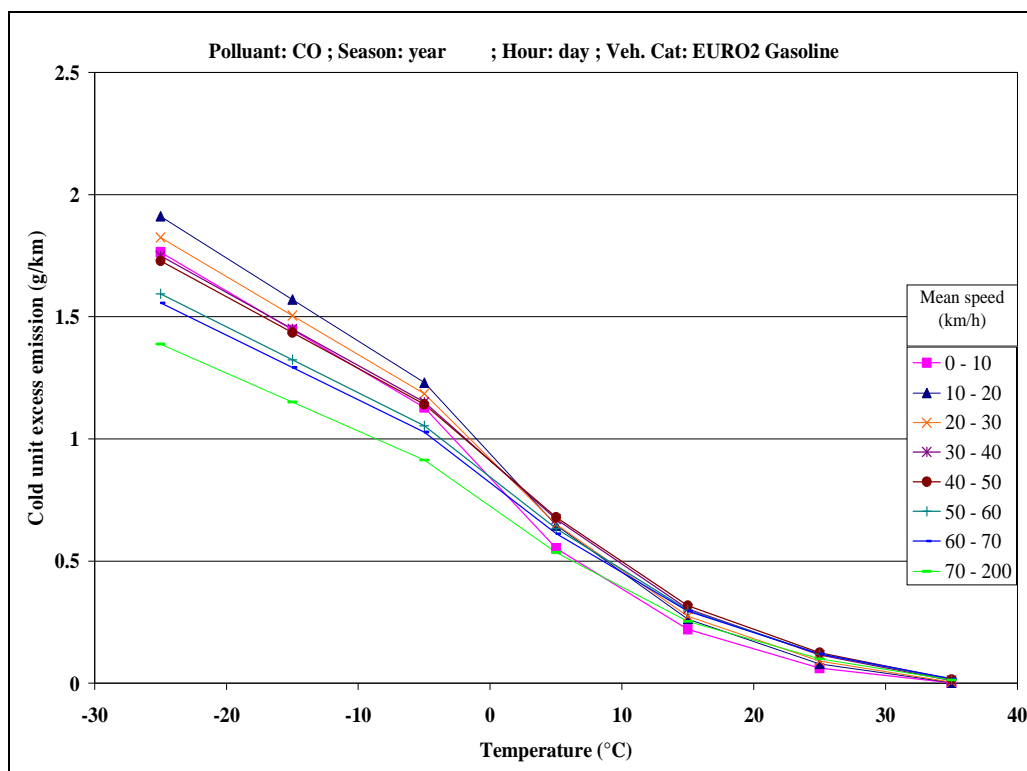


Figure 4: CO cold unit excess emission by average speed and vehicle technology.

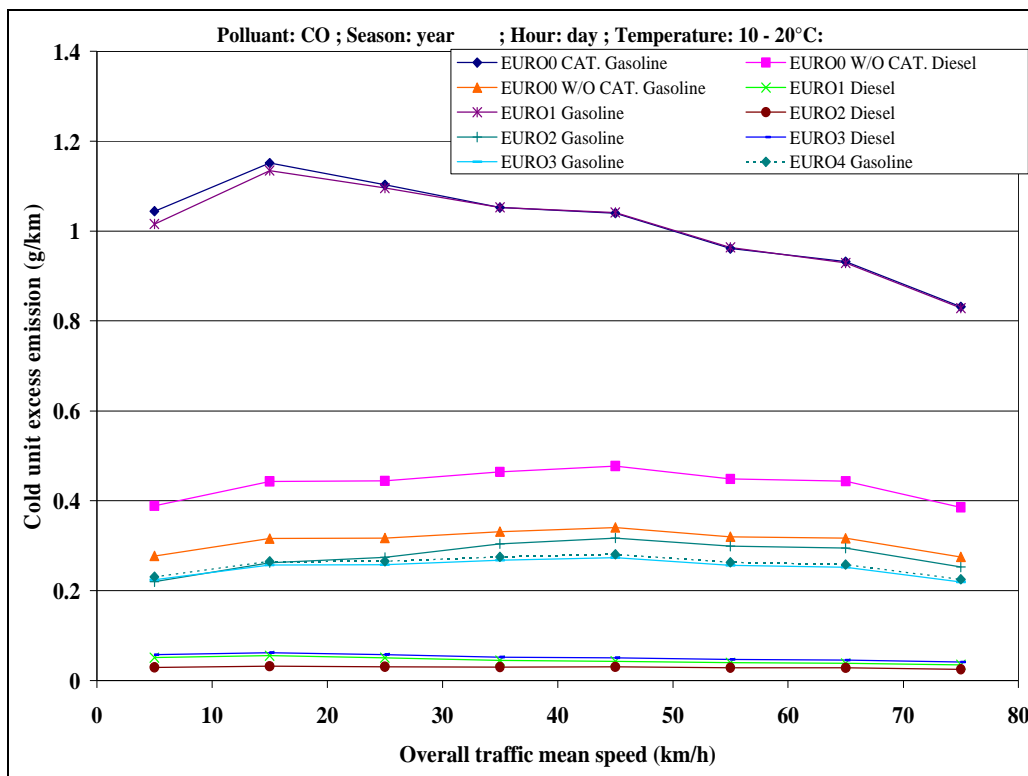


Figure 5: CO cold unit excess emission by ambient temperature and average speed (petrol Euro II).

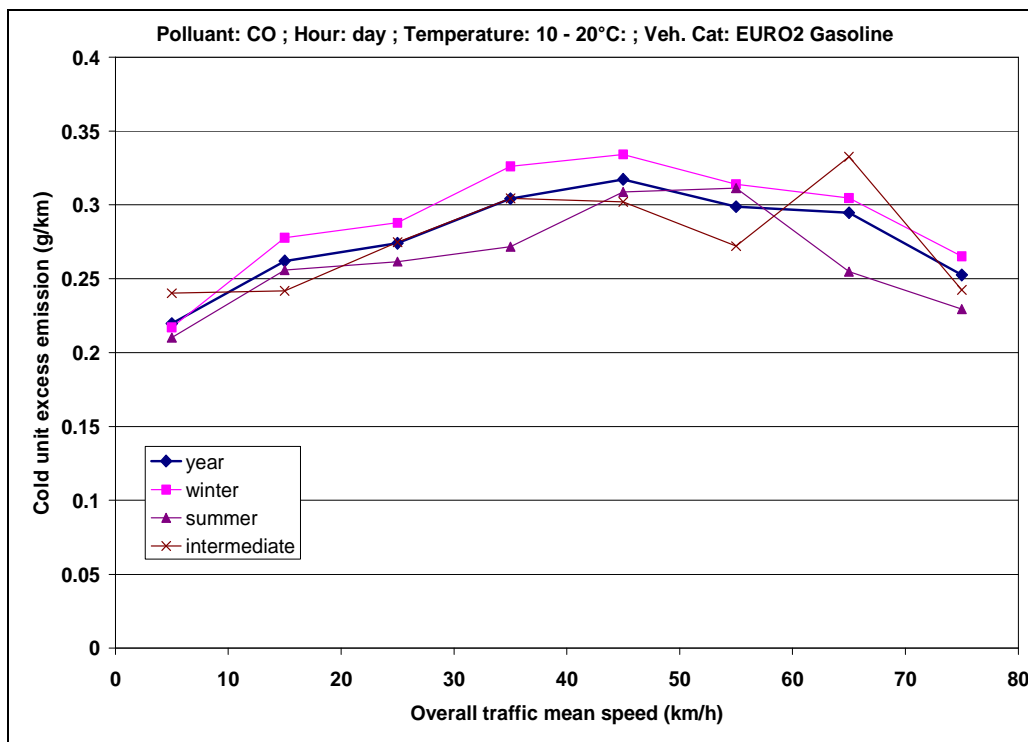


Figure 6: CO cold unit excess emission by season and average speed (petrol Euro II).

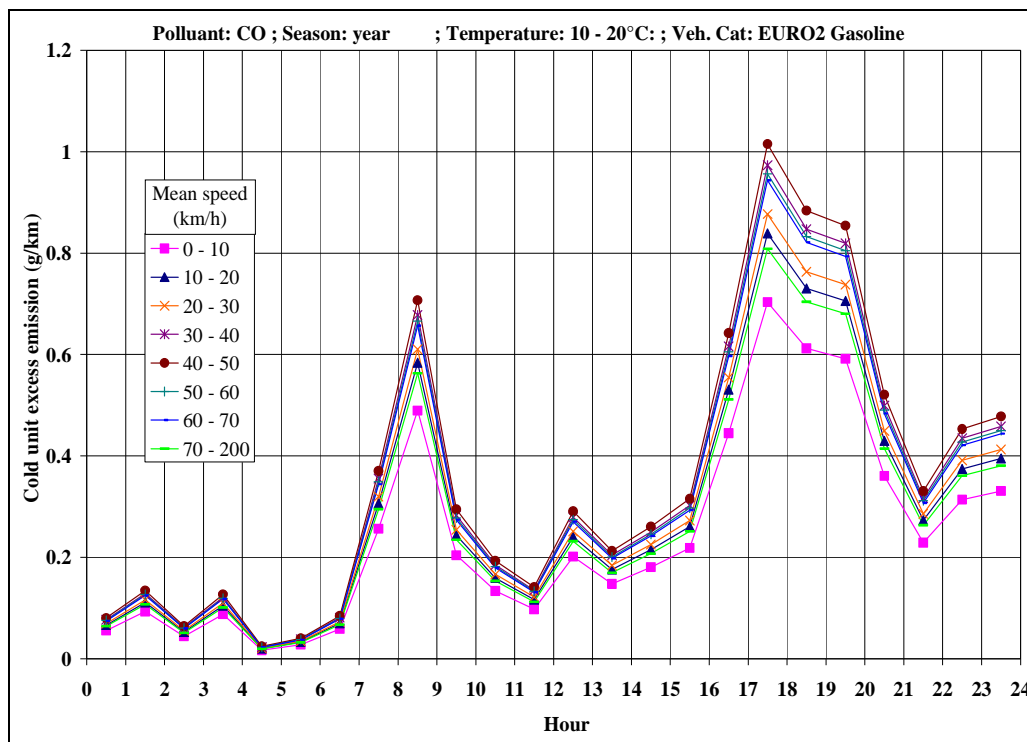


Figure 7: CO cold unit excess emission by hour and average speed (petrol Euro II).

The ARTEMIS model represents the state-of-the-art in the modelling of cold-start emissions. However, André and Joumard (2005) suggest that the model could be improved in a number of ways. For example:

- The model could be updated using new data when available, either for the most recent passenger cars, for light commercial vehicles, or for heavy-duty vehicles.
- Cross-distributions for different speeds and ambient temperatures would improve the model's precision.

The quantity of data in the model could be increased, especially for different speeds, low or high temperatures, and unregulated pollutants.

For motorcycles new cold-start emission factors were also determined in the ARTEMIS project (Elst *et al.*, 2006).

PHEM

PHEM estimates fuel consumption and emissions based on the instantaneous engine power demand and engine speed during a driving pattern specified by the user. After building and testing the model for hot exhaust emission it was decided to expand PHEM for simulating cold-start emissions. The initial effort focussed on modelling cold-start emissions from passenger cars, and particular attention was paid to the designing a method which was valid for simulating cold starts under any driving conditions and ambient temperature - a feature which usually has not been covered by other emission models (Engler *et al.*, 2001).

3.5 Current UK methodology

The NAEI procedure for estimating cold-start emissions is essentially taken from COPERT II (Ahlvik *et al.*, 1997). However, The various equations and coefficients do not appear to have been updated following the release of COPERT III or COPERT 4.

The methodology is used to estimate annual UK cold-start emissions of NO_x, CO and NMVOCs from petrol and diesel cars and LGVs. Emissions are calculated separately for catalyst and non-catalyst petrol vehicles.

Fewer cold-start emissions data are available for heavy-duty vehicles, and these are assumed to be negligible. Cold-start emissions of unregulated pollutants are not calculated. Scaling factors are applied to estimate the change in cold-start emissions due to fuel quality in a given year.

Emissions are calculated for the one-year period covered by the inventory, and shorter time periods are not considered. The equations are used with an annual mean temperature for the UK of 11°C, which is based on historic trends in Meteorological Office data for ambient temperatures over different parts of the UK. An average trip length for the UK of 8.4 km is used. All cold-start emissions are assumed to apply to urban driving.

Estimates of the distances travelled by vehicles whilst producing cold-start emissions are available for cars by average trip length and trip type (in Great Britain). Cold-start emissions are assumed to have similar characteristics in Northern Ireland. The trip types used in the calculations are classified as 'home to work', 'home to other locations' and 'work-based'. 'Home to work'-related emissions are distributed across the UK using detailed information on modal choice. Emissions for trips from home to other locations are mapped using data on car ownership. Cold-start emissions are then mapped according to the percentage assigned to each type of trip. Work-based cold-start emissions are mapped using distributions of employment across the UK (King *et al.*, 2006). The data used to create the distribution grid are based on statistics provided by the Inter Departmental Business Register (IDBR).

The basic calculation procedure for cold-start emissions currently used in the NAEI could be a source of significant error in the estimate of emissions from road transport in the UK (Barlow *et al.* 2001). Potential weaknesses in the cold-start emission methodology include the following:

- The approach is based on the equations and coefficients from COPERT II. These are now rather old data, and were updated in 2000 in COPERT III. A draft version of the COPERT 4 methodology (December 2008) is now available.
- The NAEI does not include cold-start emission estimates for heavy-duty vehicles (considered to be negligible) and motorcycles (presumably to the lack of data).
- The cold-start emission factors currently in use have been obtained using either the 6 km-long US FTP cycle or the 4 km-long ECE 15 cycle. These emission factors calculated using this data will be different to the emissions produced when travelling at distances other than this. For example, most journeys in the UK are of short duration and take place in urban areas. These journeys will start (and many of them will end) with the vehicle significantly below its normal operating temperature.
- The NAEI emission factors relate to starts conducted with the engine and catalyst components at the prevailing ambient temperature. However, the component temperatures will take time to gradually cool down to the ambient level. These will usually be somewhere intermediate between the operating and ambient temperature and dependant on length of time since the vehicle was last used. As a consequence the simple application of the NAEI of the cold-start penalty to two thirds of all trips may not accurately allow for the occurrence of many starts from intermediate temperatures.

3.6 Summary

The ARTEMIS cold-start models for passenger cars represent the state-of-the-art at the present time. The models take into account the average speed, ambient temperature, travelled distance and parking duration, as well as other parameters, and can be applied at different geographic scales. Cold-start emission data are also now available for a wide range of VOCs and PAHs, but data on PM emissions remain very limited.

However, discussions relating to the implementation of the ARTEMIS cold-start model in national inventories are still in progress. Furthermore, the ARTEMIS cold start models are used to actually *generate* emission factors, based on country-specific input data. The collection of data specifically for this purpose has not yet been conducted for the UK.

The main issues relating to the use of the ARTEMIS models in the NAEI are their complexity and the availability of relevant input data. The full ARTEMIS model currently takes several hours to process the required input data.

It is not possible to give new emission factors for the most recent LDV and HDV categories at this stage. For motorcycles, on the other hand, cold-start emission factors have been determined in the ARTEMIS project, and these are available for use in the NAEI.

4 Evaporative emissions

4.1 Background

Data from the 2004 NAEI¹⁵ indicated that 19% VOC emissions from petrol-engined road vehicles in the UK were produced by evaporation. Evaporative emissions from diesel vehicles are negligible due to the presence of heavier hydrocarbons and the extremely low volatility of diesel fuel. However, evaporative emissions from road transport were only responsible for around 2% of total emissions of VOCs in the UK. Nevertheless, several hydrocarbon compounds are associated with direct health effects, and also contribute, via chemical reactions with NO_x in the presence of sunlight, to the formation of photochemical smog. Evaporative emissions are almost exclusively a summer problem due to their sensitivity to ambient temperature (Hausberger *et al.*, 2005).

Prior to 1993 evaporative losses from petrol passenger cars were not controlled in most European countries. In the European Union, a limit value of 2.0 grammes of HC per test was first introduced by Directive 91/441/EEC (Euro 1 and Euro 2 vehicles). In order to meet this limit the installation of small on-board carbon canisters was necessary. Directive 91/441/EC was superseded by Directive 98/69/EC, applicable to Euro 3 and Euro 4 vehicles. The limit value for evaporative emissions remained at the same level, but the evaporative emissions testing procedure increased in severity. The introduction of larger carbon canisters was necessary to comply with these more stringent requirements. In spite of the tightening of emission standards, improvements in vehicle technology, and petrol regulations, the problem of evaporative emissions remains. This is mainly due to the continuing presence of older, uncontrolled vehicles, vehicles with defective evaporative control systems, motorcycles and a variety of recreational vehicles (Hausberger *et al.*, 2005).

There are five mechanisms by which petrol fuel evaporates from vehicles:

Diurnal emissions: The increase in ambient temperature which occurs during the daylight hours results in the thermal expansion of the fuel and vapour in the petrol tank. Without an evaporation control system some of the increased volume of fuel vapour is vented to the atmosphere. At night when the temperature drops the vapour contracts and fresh air is drawn into the petrol tank through the vent. This lowers the concentration of hydrocarbons in the vapour space above the liquid petrol, which subsequently leads to additional evaporation. The overall mechanism is also known as 'tank breathing'.

Hot-soak emissions: When a vehicle is parked and the engine is turned off, there is a transfer of heat from the engine and exhaust system to the fuel system (in which fuel is no longer flowing). The increase in the temperature of the fuel leads to evaporation. Older cars which are equipped with carburettors and float bowls have significant hot-soak emissions. For the modern vehicle fleet this mechanism is responsible for only a small proportion of evaporative emissions.

Running emissions: These are defined as the evaporative emissions which occur whilst a vehicle is being driven. The heat emitted from the engine/exhaust and the changing wind strength result in variations in the temperature of the fuel system. Running emissions are most significant during periods of high ambient temperature. The combined effect of high ambient temperature and engine/exhaust system heat, as well as any heated fuel which is returned to the tank from the engine, can generate a significant amount of vapour in the fuel tank.

Resting emissions: These are identified as a separate evaporative source in some studies. Resting emissions result from diffusion, permeation, seepage and minor liquid leaks, and do not need an increase in fuel temperature to occur. Where resting emissions are not considered as a separate category they can be included in the hot-soak and diurnal categories.

Refuelling emissions: These occur whilst the fuel tank is being filled and the saturated vapours are displaced and vented into the atmosphere. Vapour recovery systems can be used at filling stations to control refuelling emissions. However, refuelling emissions are usually attributed to the fuel handling and distribution chain rather than to the vehicle, and were therefore not addressed in this project.

¹⁵ http://www.naei.org.uk/emissions/emissions_2004.php?action=unece&options=1P1Y

Evaporative emissions are modelled in the NAEI using data and methodologies which are now rather old and are due for revision. However, until recently few new measurements of evaporative emissions had been conducted in Europe, and therefore models had not been updated. The most significant recent measurements and model developments have been the following:

- The European Commission's Fifth Framework project ARTEMIS (Hausberger *et al.*, 2005).
- The EUCAR/JRC/CONCAWE joint programme on evaporative emissions from petrol cars (Martini *et al.*, 2007). The objectives of this study were to investigate the impacts of the addition of ethanol to petrol on evaporative emissions from cars, and to provide revised and validated emission factors for evaporative emissions.
- The release of a draft update (version 4) of COPERT (COmputer Programme to calculate Emissions from Road Transport) in July 2007. COPERT 4¹⁶ takes into account the ARTEMIS and EUCAR/JRC/CONCAWE work.

The objectives of this part of the work were to examine recent methodological developments and provide recommendations for the NAEI. Latham and Boulter (2009b) described the control and measurement of evaporative emissions, and summarised the findings of the EUCAR/JRC/CONCAWE joint programme

A number of basic comparisons were made between the predictions of the NAEI, ARTEMIS and COPERT 4 (simple 'Tier 2' method only) models. The following between-model comparisons were made:

- Emission factors for diurnal, hot-soak and running emissions for different types of vehicle.
- Fleet-weighted annual emission factors (for an average UK vehicle in 2007) for diurnal emissions, hot-soak emissions, running emissions and total emissions.

Failures of evaporative emission-control systems were not taken into account.

4.2 Modelling assumptions

The vehicle categories used in the three models are not equivalent, and therefore several assumptions were required. Furthermore, in order to calculate total annual emission factors on the same basis, a correspondence with the national UK fleet data had to be established. To calculate the weighted emission factors the UK fleet data were taken from the NAEI website¹⁷. For pre-Euro 1 vehicles in the COPERT 4 model a distinction is made between those equipped with a carburettor and those equipped with fuel injection. It was assumed that 1% of pre-Euro 1 vehicles had fuel injection. In the case of two-wheel vehicles, no emission factors are given in the NAEI and the COPERT 4 model is considerably more detailed than the ARTEMIS model. Consequently, no comparisons for these vehicles were made.

In the NAEI evaporative emissions are calculated using monthly average temperature and RVP¹⁸ data. However, for the basic model comparison presented here, only annual average values were used. The temperature data for 2003 and beyond, and the RVP data for 2005 were used. These were supplied to TRL by UKPIA (Watson, 2007). The average daily temperature was 10.2°C, and the average RVP was 85.2 kPa.

In the ARTEMIS model an average emission factor for running emissions for UK petrol cars was estimated by weighting the emission factors for urban, rural and motorway driving by the proportions of vehicle mileage in each road category, based on data from the Department for Transport *et al.* (2005). For COPERT the emission factors for the summer and winter temperature ranges of 10-25°C and 0-15°C were used.

4.3 Results

The results of the comparisons are summarised below. It should again be noted that these calculations are based on rather crude assumptions and annual average statistics. However, although the precise findings will change if a more detailed method is used the authors consider it unlikely that the general conclusions will be affected.

¹⁶ <http://lat.eng.auth.gr/copert/>

¹⁷ http://www.naei.org.uk/datachunk.php?f_datachunk_id=9

¹⁸ RVP = Reid vapour pressure.

4.3.1 Emission factors

Diurnal emissions

The diurnal emission factors in the three models are stated in $\text{g vehicle}^{-1} \text{ day}^{-1}$. Vehicles without evaporative emission-control systems have substantially higher diurnal emissions than controlled vehicles. However, the majority of vehicles on UK roads now contain such controls, and therefore uncontrolled emissions are gradually becoming less important as these vehicles are phased out.

Resting emissions are not explicitly defined in the NAEI and COPERT 4, but may be implicitly allowed for in the diurnal emissions category. Therefore, diurnal and resting emissions are assumed to constitute a combined diurnal emission (as defined in ARTEMIS) for the purposes of this comparison.

The emission factor for diurnal emissions from pre-Euro 1 vehicles in the ARTEMIS model was around 20% higher than that for uncontrolled vehicles in the NAEI. For Euro 1 and Euro 2 vehicles, the ARTEMIS emission factor was around 35% higher than that for uncontrolled vehicles in the NAEI. However, the ARTEMIS emission factor for Euro 3 and 4 vehicles was much lower than that for controlled vehicles in the NAEI. This indicates that the NAEI method could be further refined by introducing a more detailed vehicle classification system for evaporative emissions. The diurnal emission factors in COPERT 4 were much lower than those in ARTEMIS and the NAEI.

Hot-soak emissions

The hot-soak emission factors for uncontrolled vehicles were much higher than those for controlled vehicles. The ARTEMIS model predicted that pre-Euro 1 vehicles had 80% higher hot-soak emissions than the equivalent uncontrolled category in the NAEI. For controlled vehicles, however, ARTEMIS had lower emission factors. COPERT 4 had higher hot-soak emission factors than the other models for uncontrolled vehicles, but the emission factors for controlled vehicles were of a similar magnitude to those for Euro 3 and 4 vehicles in ARTEMIS. It should be noted that COPERT 4 also included 'cold and warm soak' for vehicles with a carburettor. When these were excluded the COPERT emission factors were reduced by around 40-50%, but were still higher than those in the other models.

Running emissions

The running emission factors in the NAEI and ARTEMIS could be compared directly, as they were stated in $\text{g vehicle}^{-1} \text{ km}^{-1}$. However, the COPERT emission factors were stated in $\text{g vehicle}^{-1} \text{ trip}^{-1}$. Again, COPERT 4 also included 'cold and warm soak' for vehicles with a carburettor, but in this case the contribution to the total emission factor was proportionally smaller (15% for uncontrolled vehicles). There were some rather large differences between the running emission factors in ARTEMIS and those in the NAEI, with the most pronounced difference being the much larger emission factor (50 times higher) for uncontrolled (pre-Euro 1) vehicles in ARTEMIS. The average trip length used in the NAEI is 8.4 km. When this value was applied the ARTEMIS emission factor for uncontrolled vehicles was slightly lower than those in COPERT 4. The values for controlled vehicles in ARTEMIS were, on the other hand, around three times higher on average. Both the ARTEMIS and COPERT emission factors were considerably higher than those used in the NAEI.

4.3.2 Fleet-weighted emission factors

The diurnal, hot-soak and running emission factors were combined by weighting the emission factors for each vehicle category according to the composition of the 2007 fleet, and converting the three sources into annual mass emissions. This was achieved, in the case of hot-soak emissions (and running emissions in the case of COPERT 4), by multiplying the emissions per trip by the annual number of trips. The number of trips per year was obtained by dividing the average annual distance travelled (assumed to be 10,000 miles) by the average trip length. Running emissions were converted by multiplying by the average annual distance travelled. The average distance per year for petrol cars was provided by Li (2006), and the average petrol car trip length was based on data for 1999-2001 (Department for Transport, 2003). The overall results are shown in Figure 8.

The total fleet-weighted annual emission factors in the three models were rather similar, ranging from around 2.5 to 3 $\text{kg vehicle}^{-1} \text{ year}^{-1}$. This was in spite of the fact that the relative contributions of diurnal, hot soak and

running emissions in the three models were very different. In particular, running emissions in the NAEI, and diurnal emissions in COPERT 4, were very low compared with the other models.

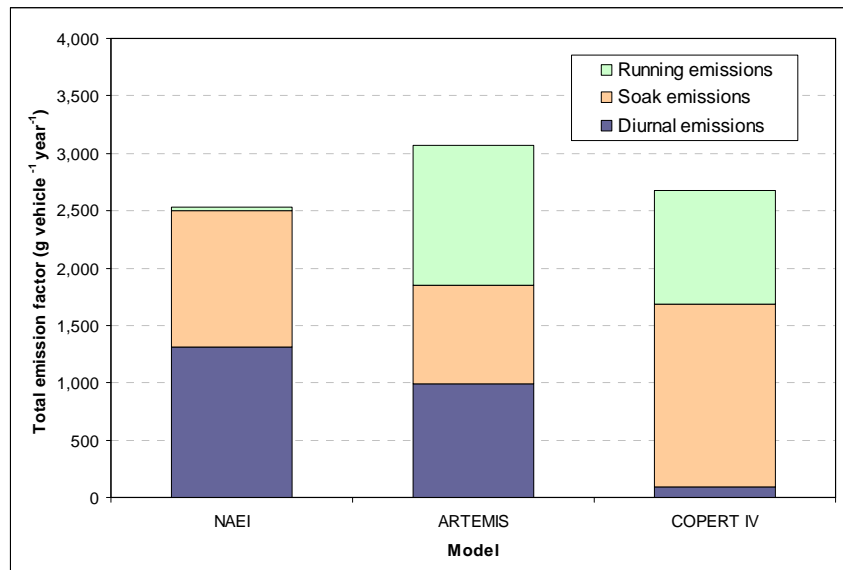


Figure 8: Fleet-weighted annual emission factors in the NAEI, ARTEMIS and COPERT 4 methods.

5 Demonstration of new methodology

A spreadsheet has been developed to demonstrate the new hot exhaust emission factors (*EmissionFactors_Demo (15-May-09).xls*). This spreadsheet includes the following:

- The new emission factors for regulated pollutants and fuel consumption.
- The mileage and fuel scaling factors.
- Typical vehicle mileages.

Also included in the spreadsheet are data on the national fleet composition for the years 1996 to 2025.

5.1 Input data

The input data requirements are shown in Figure 9. The user must enter the year and the length of the road in the yellow boxes shown. For each of the vehicle categories, the user then enters the number of vehicles and the corresponding average speed. The vehicle flows can be hourly or daily, depending on the user requirements. In addition, the user has the option (not shown) of including the mileage and fuel scaling factors.

Year (1996 to 2025):		2009
Road length:		500 m
	Number of vehicles	Average Speed km/h
Cars	5000	50
Taxis	500	45
Vans	2000	50
Rigid HGVs	500	45
Artic HGVs	300	45
Buses	100	30
Coaches	50	45
Moped	100	45
Motorcycles	300	60

Figure 9: Demonstration spreadsheet - input data.

5.2 Results

Once the input data have been entered the results are updated. The spreadsheet calculates the emission factors for each vehicle category, as shown in Figure 10. These calculations include the fleet composition for the year selected, the speed entered and, where selected, the mileage and fuel scaling factors.

These emission factors are multiplied up by the number of vehicles and the length of the road to give the emissions per vehicle category along the road, as shown in Figure 11. The emissions from the vehicle categories are also summated to give the total emissions from the traffic on the road. The time period is defined by the traffic flow input – e.g. if the flow data are per hour then the emissions are per hour.

Fleet-weighted emission factors per vehicle						
	CO g/km	HC g/km	NOx g/km	PM g/km	uCO₂ g/km	FC l/100km
Cars	0.788	0.059	0.263	0.014	154.61	6.30
Taxis	0.222	0.041	0.614	0.048	199.45	7.39
Vans	0.237	0.027	0.433	0.032	154.11	5.75
Rigid HGVs	0.917	0.161	4.138	0.072	525.02	19.44
Artic HGVs	1.249	0.233	7.285	0.118	947.42	35.09
Buses	1.670	0.369	8.197	0.175	939.39	34.79
Coaches	1.347	0.353	7.208	0.155	833.42	30.86
Moped	8.840	8.068	0.026	0.123	61.43	2.58
Motorcycles	14.135	1.806	0.222	0.040	96.69	4.06

Figure 10: Demonstration spreadsheet – results 1 – emission factors.

Total emissions along road						
	CO kg	HC kg	NOx kg	PM kg	uCO₂ kg	FC litres
Cars	1.970	0.148	0.658	0.035	386.53	157.57
Taxis	0.055	0.010	0.154	0.012	49.86	18.46
Vans	0.237	0.027	0.433	0.032	154.11	57.50
Rigid HGVs	0.229	0.040	1.035	0.018	131.25	48.61
Artic HGVs	0.187	0.035	1.093	0.018	142.11	52.63
Buses	0.083	0.018	0.410	0.009	46.97	17.39
Coaches	0.034	0.009	0.180	0.004	20.84	7.72
Moped	0.442	0.403	0.001	0.006	3.07	1.29
Motorcycles	2.120	0.271	0.033	0.006	14.50	6.09
Total	5.359	0.963	3.997	0.139	949.25	367.26

Figure 11: Demonstration spreadsheet – results 2 – total emissions.

6 Conclusions and recommendations

The conclusions and recommendations from the projects are summarised below by topic.

6.1 Hot exhaust emissions

Driving cycles

1. For cars, the driving cycles in the 2002 UKEFD adequately cover the range of driving characteristics observed in the real world. However, a small number of UKEFD driving cycles appear to have average positive and negative accelerations which are outside the range of real-world conditions. The possibility of replacing these cycles with other cycles from the Reference Book, and using the latter to fill gaps in the UKEFD, should be considered for future test programmes.
2. For LGVs the database of real-world driving patterns is more limited, although the cycles used in the current UKEFD appear to cover the range of driving characteristics which are likely to be encountered. However, as with cars some UKEFD cycles may have average accelerations which are not realistic for the UK. Again, the use of alternative cycles should be considered in future tests.
3. The WSL cycles do not appear to reproduce the aggressiveness of driving for cars and LGVs, and do not cover the highest speeds encountered on the road. A more representative set of driving cycles should therefore be considered for future testing. Alternatively, the WSL cycles could be retained, but supplemented with some high-speed cycles, and cycles which have higher average accelerations and decelerations.
4. In the case of HGVs, some of the UKEFD driving cycles have relatively high accelerations and rapid decelerations which are not apparent in real-world driving patterns.
5. Urban buses operate at relatively low speeds, and may be unable to attain the higher speeds required for some of the cycles. Coaches, on the other hand, are likely to operate at higher motorway speeds. Urban buses and coaches should therefore be treated separately when deriving emission factors, and more representative driving cycles for these vehicle classes should be used in the future.
6. Although some of the real-world driving patterns have average speeds lower than 10 km h⁻¹, such low speeds are not represented in the FiGE cycle (which has a minimum average cycle speed of 23 km h⁻¹). The higher-speed FiGE cycles (suburban and motorway) also appear to have low average accelerations compared with the real-world driving patterns. Again a more representative set of driving cycles should be considered for future testing.
7. For all vehicle types it appears that the driving cycles contained in the Reference Book provide a good level of coverage of different aspects of vehicle operation. It therefore appears that any new emission factors for use in the UK could be based on driving cycles which are included in the Reference Book, and there is no need for new cycles to be developed.

Test parameters

8. When compiling an emission factor database, correction factors should ideally be applied to account for, for example, the gear-shift strategy, vehicle mileage and ambient air temperature.
9. As emission models are constructed primarily using bag samples, and there remain some artefacts in continuous measurements which are difficult to correct, there appears to be little justification for routinely including continuous emission measurements in the tests used for emission factor development. This recommendation does not apply to *ad hoc* tests for the evaluation of technical and/or policy measures, for which continuous measurements may be beneficial. Where continuous measurements are taken, a high temporal resolution (*e.g.* 10 Hz) is recommended, and some effort ought to be made to correct the continuous signals. For this purpose, a number of experimental settings will need to be recorded.

10. The work conducted within ARTEMIS addressed a wide range of different topics relating to emissions from two-wheel vehicles. Nevertheless, a number of issues remain for future investigation, and some recommendations were given by Elst *et al.* (2006). These included the following.
 - Real-world data should be recorded for a wider variety of vehicles to obtain more representative driving patterns.
 - A detailed system of vehicle categorisation could be defined for in-use motorcycles. However, the more detailed the categorisation the more vehicles need to be measured to obtain robust emission factors. The actual categorisation should therefore be adapted to the number of available emission results.
 - A detailed measurement protocol which defines the measurement procedure and a standard test report template are vital for assuring comparability of measurements carried out by different laboratories. The presence of a test-witness who is aware of the measurement procedure and preparative actions, bag analysis and data processing could even improve quality and comparability of the obtained emission results.
 - It is recommended that test drivers become acquainted to the test cycle and the specific behaviour of the two-wheel vehicle to be tested.
 - Two-wheel vehicles obtained from dealers, rental companies and importers are generally well maintained and relatively new. Such vehicles are not recommended when addressing topics such as the effects of tampering or deterioration.
 - A dedicated measurement programme should be developed to address fuel effects.
 - It is recommended that a dedicated test programme be conducted in order to obtain a more detailed understanding of the effects of inspection and maintenance.

Model assessment

11. Several alternative models for estimating hot exhaust emissions could be used in the NAEI. Some of these (*e.g.* COPERT and ARTEMIS) essentially use the same modelling approach (*i.e.* average speed), and could therefore be introduced with only minor changes to the activity data (model inputs). However, the introduction of a different type of model (*e.g.* traffic situation) would require considerably more work, as the activity data would have to be reconfigured and transport statistics would have to be analysed differently.
12. Various average-speed and traffic situation models were compared with the NAEI model, including COPERT III, ARTEMIS and HBEFA. Generally, there was a very good agreement between the shapes of the emissions curves in the NAEI and with the various models tested, but the results varied with vehicle category and pollutant. The best agreements between the models appeared to be for NO_x and CO₂. For CO and HC, most of the comparisons showed a poorer agreement, with PM being intermediate.
13. In an attempt to determine the accuracy of the predictions of emission models, model predictions were compared with (i) on-board emission measurements, (ii) remote sensing measurements, (iii) the results from the inversion of an air pollution model and (iv) measurements in road tunnels. The assessments included errors, assumptions and limitations which made it difficult to make general conclusions. Moreover, it is unlikely that such approaches could be conducted with enough regularity or consistency to enable changes in the accuracy of emission models to be checked with time. However, the results did indicate that the current UK emission factors probably provide a reasonably accurate characterisation of *total* emissions from road transport, and broadly agree with the predictions of other models used in Europe. Nevertheless, the emission factors for some specific vehicle types are associated with a high degree of uncertainty, not least due the difficulties associated with correctly identifying vehicle types and their operation.
14. Given the above conclusions, there seems to be little justification at present for replacing the current emission calculation method in the NAEI, but the emission factors for specific vehicle categories should be improved where possible. Further efforts are also required to categorise vehicles appropriately, and to properly characterise operational conditions (such as road gradient and load in the case of HDVs).

15. As the NAEI average-speed functions are used not only for the national inventory but also for local air pollution modelling, the accuracy of different models in this latter context should also be considered. Based upon the data presented here, and given the other uncertainties associated with estimating pollutant concentrations in ambient air, it cannot be stated with confidence that any one emission model is more accurate than any other. Modellers should attempt to characterise emissions in a manner which is appropriate to the assessment being conducted, and in as much detail as possible given the available resources.

Effects of fuel properties

16. 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.
17. 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.
18. 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
19. 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 CO₂ emissions appear not to be greatly affected. However, there appear to be few recommendations for specific adjustment factors.

New emission factors – regulated pollutants

20. The main enhancements in the 2009 update to the existing hot exhaust emission factors for regulated pollutants include the following:
 - The addition of fuels other than petrol and diesel for LDVs.
 - The addition of Euro 5 and Euro 6 LDVs.
 - The inclusion of taxis (black cabs) as a separate category.
 - The sub-division of rigid HGVs, articulated HGVs, buses and coaches by weight band.
 - The addition of Euro V and Euro VI HDVs.
 - The sub-division of two-wheel vehicles into mopeds and motorcycles.
 - The sub-division of motorcycles by engine size band.

These changes should enable more detailed and accurate calculations to be made, and provide greater flexibility in terms of scenario testing.

One aspect that received limited review within this project was the issue of emission factor uncertainty. Whilst the expansion of the emission database used in the derivation of the emission factors will improve the robustness of emission estimates for pre-Euro 3 vehicles, significantly fewer data are available for more recent Euro emission classes. Therefore the uncertainty of emissions associated with the newest vehicle classes is likely to be higher. It is recommended that an assessment of data uncertainty and robustness is undertaken.

New emission factors - carbon dioxide

21. For most categories of petrol and diesel car the CO₂ emission functions which were derived from the LDV-regulated database showed little or no difference between all Euro categories. However, type approval data for new cars, and publications by the European Commission and car manufacturers, indicate that new car CO₂ emissions are decreasing with time. Consequently, and again at the request of DfT, an alternative approach to generating CO₂ emission functions was used which took into account the reduction in emissions from new cars. The validity of this approach should be tested once more emission data for Euro 5 and Euro 6 technologies become available.

New emission factors - unregulated pollutants

22. The unregulated pollutants considered were CH₄, 1,3-butadiene, benzene, N₂O, NH₃, PAHs, NO₂ and PM size fractions. Emission factors were based on a combination of UK test data and information from COPERT 4. However, significant discrepancies exist between the different data sets.
23. Emission factors were calculated according to the availability of data. Average-speed functions could only be derived for methane and benzene, and even in these cases only for petrol and diesel light-duty vehicles. The possibility of developing average-speed functions for other vehicle categories and pollutants should be considered when further data become available.
24. For two-wheel vehicles no emission factors were available for 1,3-butadiene and benzene. For LPG cars no emission factors were available for benzene and ammonia. Again, emission factors should be developed when suitable data become available.
25. There were a number of inconsistencies and general 'difficulties' associated with the data. This has often been observed in the past with unregulated pollutants, and is one reason why the analysis of these pollutants is so problematic.

Scaling factors – vehicle mileage

26. Mileage scaling factors for cars and LGVs were determined from the database of emission measurements compiled within the project. However, this is not an altogether straightforward process, as different scaling factors are required for different years, and information is required on the average accumulated mileage of different types of vehicle by year. There is some scope for refining the approach in the future.
27. The database of heavy-duty emission factors compiled in this project was considered to be too small to allow deterioration effects to be examined. As a consequence of this, and taking into account the findings of the ARTEMIS project, no mileage scaling factors were developed for heavy-duty vehicles.
28. No emission degradation functions were available for two-wheel vehicles. This was identified as an area for further research.

Scaling factors -fuel composition

29. In order to derive fuel composition scaling factors, an adapted version of the method presented in COPERT III/IV was used. The resulting scaling factors should be used in conjunction with the basic 2009 emission factors.

Scaling factors – biofuels

30. No scaling factors for biofuels have been provided here. This should be reviewed as and when new information is published or new legislation is introduced.

6.2 Cold-start emissions

31. The main conclusion from the work on cold start emissions is that the current NAEI model, which is based upon COPERT II, ought to be updated to take into account new data and modelling approaches.

32. A more detailed examination of the ARTEMIS models would be required before one of them could be incorporated into the NAEI. For example, a survey of parking duration may be necessary to make full use of the ARTEMIS models capabilities. Alternatively, it may be possible to simplify the models so that most of the important variables are included. If a single cold-start factor was required for each vehicle class (independent of vehicle speed), this could also be calculated using an average trip distance and speed, but it would mean that much of the data generated in the ARTEMIS programme would be ignored.
33. Before any more detailed modelling of cold-start emissions is attempted - the current NAEI model (which is based upon COPERT II) ought to be updated to reflect COPERT 4. COPERT 4 does not contain any new emission factors.
34. In fact, at the time of writing the compilers of COPERT were improving the methodology for cold-start emissions. In addition, a revised cold-start model for the Handbook of Emission Factors ought to be available in 2009. When these are published they should also be considered for inclusion in the NAEI.

6.3 Evaporative emissions

35. The main conclusion of this work is that, given that considerable effort has been put into developing the new method in COPERT 4 and the flexibility it offers, there would be sufficient justification for changing the NAEI to include this method. This project has only examined the Tier 2 version of COPERT 4. Further work is required to assess the applicability and reliability of the detailed Tier 3 method in COPERT 4.
36. Allowance should also be made in the NAEI for the failure of evaporative control systems. Again, the detailed method of COPERT 4 allows for this. However, there is little or no information on the actual proportion of in-service vehicles in the UK which have failures. This is an area which requires further investigation.
37. In view of the large discrepancies between the predictions of running and diurnal emissions, there is a case for examining these sources in more detail and, if necessary, performing further validation tests. However, running emissions may be heavily dependent upon the condition of the vehicle (*i.e.* whether it has leaks in the fuel system, lubrication or exhaust system which could be detected during an evaporative emissions test, and obtaining a reliable statistical sample may be difficult and expensive.
38. It is also noted that vehicles which have failures in the evaporative emissions-control system are classed as having pre-Euro 1 evaporative emission levels in the ARTEMIS model. Although failures were not specifically addressed in this work it is more likely that failures are partial, and that this assumption is too severe.

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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 5 th 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).
CH₄	Methane.
CO	Carbon monoxide.
CO₂	Carbon dioxide.
uCO₂	'Ultimate' CO ₂ . This assumes that all carbon in vehicle exhaust (i.e. from CO ₂ , CO, HC and PM) is ultimately found as CO ₂ in the atmosphere).
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	<u>C</u> omputer <u>P</u> rogram to calculate <u>E</u> missions from <u>R</u> oad <u>T</u> ransport. 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 (<i>e.g.</i> 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>i.e.</i> 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: <i>The inspection of in-use cars in order to attain minimum emissions of pollutants and optimum energy efficiency</i> , 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 4 th 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.
N₂O	Nitrous oxide.
NH₃	Ammonia.
NMVOC	Non-methane volatile organic compounds.
NO	Nitric oxide.
NO₂	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.
PM₁₀	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 (<i>e.g.</i> urban, rural), the functional type (<i>e.g.</i> 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.
SO₂	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 (<i>e.g.</i> 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.