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Emission factors 2009: Report 2 – a review of the average-speed approach for estimating hot exhaust emissions

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TRL Limited

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Emission factors 2009: Report 2 - a review of the average-speed approach for estimating hot exhaust emissions

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Executive summary

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

In the case of 'hot' exhaust emissions -which occur when the engine and any after-treatment devices have reached their full operational temperatures - the current UK emissions factors for regulated pollutants, and for some non-regulated pollutants, are defined as functions of average vehicle speed over a trip. This may not be the best approach in some circumstances, and other means of characterising vehicle emissions performance may be more accurate. The overall aim of this Report was to review the use of average vehicle speed to characterise hot exhaust emissions and to provide recommendations for the NAEI.

Several specific models for estimating hot exhaust emissions could be used in the NAEI, based on aspects such as availability, cost, coverage of pollutants and vehicle categories, robustness, and ease of use. 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 traffic situation model would require considerably more work, as the activity data would have to be reconfigured and transport statistics would have to be analysed differently.

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 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 CO_2. For CO and HC, most of the comparisons showed a poorer agreement, with PM being intermediate.

Four types of assessment were considered in an attempt to determine the accuracy of the predictions of different models. These assessments - some of which relied upon the analysis of data, and others on information available in the literature - 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. 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. 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, and broadly agree with the predictions of other models used in Europe. However, the emission factors for 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.

There therefore 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).

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.

1 Introduction

Emissions of air pollutants in the United Kingdom are reported in the National Atmospheric Emissions Inventory (NAEI)[1]. In the NAEI 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 determine 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 is based on sound data.

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

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

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

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

This Report presents the findings of Task 2. In the case of hot exhaust emissions, the current UK emissions factors for regulated pollutants, and for some non-regulated pollutants, are defined as functions of average vehicle speed over a trip. This may not be the best approach in some circumstances, and other means of characterising vehicle emissions performance may be more accurate. The overall aim of Task 2 was to review the use of average vehicle speed to characterise hot exhaust emissions and to provide recommendations for the NAEI.

Models for estimating hot exhaust emissions are reviewed in Chapter 2. The specific method used in the NAEI is described, and potential limitations of the method are highlighted. A number of different approaches were used to evaluate the accuracy of the NAEI method and emission factors, including model comparisons (Chapter 3), validation studies such as tunnel measurements and inverse modelling (Chapter 4), and a review of uncertainty analysis studies (Chapter 5). The findings are summarised in Chapter 6, and Chapter 7 provides the conclusions and recommendations from the work.

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

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

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[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.

vehicles. For LDVs and two-wheel vehicles, Arabic numerals are used (*e.g.* Euro 1, Euro 2…*etc.*), whereas for HDVs Roman numerals are used (*e.g.* Euro I, Euro II…*etc.*).

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

2 Methods for modelling hot exhaust emissions

2.1 Overview

Atmospheric pollutants are emitted from road vehicles as a result of combustion and other processes. Exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and particulate matter (PM), as well as evaporative emissions of volatile organic compounds (VOCs), are regulated by EU Directives. The legislation, including the measurement methods and emission limits, was summarised in the Task 1 report (Boulter *et al.*, 2009). Some of the gaseous pollutants emitted in vehicle exhaust are not regulated, including the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). For exhaust pollutants, a distinction can also be drawn between 'hot' emissions and 'cold-start' emissions. Hot exhaust emissions, which are the subject of this Report, are those produced when a vehicle's engine and emission-control system are at their full operational temperatures. Cold-start emissions are those produced from the exhaust when the temperatures of the engine and emission-control system are between the ambient temperature and their full operational temperatures. Finally, PM is generated as a result of a number of unregulated non-exhaust processes, including tyre wear, brake wear, road surface wear and the resuspension of road dust.

In some countries estimates of road transport emissions have been made on a national basis and for local pollution studies since the 1970s. The models used to predict exhaust emissions have gradually been improved, mainly in terms of the amount, type and quality of data available. The legislative emission standard of a vehicle has a large influence on the actual emissions as do many other parameters, including vehicle-related factors such as model, weight, fuel type, technology level and mileage, and operational factors such as speed, acceleration, gear selection, road gradient and ambient temperature. All emission models must take into account the factors affecting emissions, although the manner and detail in which they do so can differ substantially.

Models for estimating hot exhaust emissions tend to be classified according to a combination of the geographical scale of application, the generic model type, and the nature of the emission calculation approach. The different classification approaches, with examples of specific models, are summarised in Table 1. The generic types of model are discussed in more detail in Sections 2.2, where there is also further explanation of the terms and acronyms used. The NAEI method is summarised in Section 2.3.

Table 1: Models for estimating hot exhaust emissions (Boulter *et al.*, 2005a)[4].

<table>
<tr><th colspan="2">Generic type</th><th>Example</th><th>Type of input data required to define vehicle operation</th><th>Typical application</th></tr>
<tr><td colspan="2">Aggregated emission factors</td><td>NAEI</td><td>Area or road type</td><td>Inventories, EIA[5], SEA[6]</td></tr>
<tr><td colspan="2">Average speed</td><td>COPERT,NAEI
ARTEMIS</td><td>Average trip speed</td><td>Inventories</td></tr>
<tr><td colspan="2">Adjusted average speed</td><td>TEE</td><td>Average speed, congestion level</td><td>Assessment of UTM schemes</td></tr>
<tr><td colspan="2">Traffic situation</td><td>HBEFA,
ARTEMIS</td><td>Road type, speed limit, level of congestion</td><td>Inventories, EIA, SEA, area-wide assessment of UTM[7]</td></tr>
<tr><td colspan="2">Multiple linear regression</td><td>VERSIT+</td><td>Driving pattern</td><td>Inventories</td></tr>
<tr><td rowspan="4">Modal</td><td>'Simple'</td><td>UROPOL</td><td>Data on driving modes</td><td>Assessment of UTM schemes</td></tr>
<tr><td>Speed-based, unadjusted</td><td>MODEM</td><td rowspan="3">Driving pattern, often with gradient and vehicle-specific data</td><td rowspan="3">Detailed temporal and spatial analysis of emissions</td></tr>
<tr><td>Power-based, unadjusted</td><td>VeTESS,
PHEM (HDV)</td></tr>
<tr><td>Power-based, adjusted</td><td>PHEM (PC)</td></tr>
</table>

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[4] Most of the models listed also address other types of vehicle, such as heavy goods vehicles and buses.

[5] EIA = environmental impact assessment.

[6] SEA = strategic environmental assessment.

[7] UTM = urban traffic management.

2.2 Types of model

2.2.1 Aggregated emission factor models

Aggregated emission factors (sometimes termed 'bulk' emission factors are used at the simplest level, with a single emission factor being used to represent a particular type of vehicle and a general type of driving (the traditional distinction is between urban roads, rural roads and motorways). Vehicle operation is therefore only taken into account at a very rudimentary level, and the approach cannot be used to determine emissions for situations which are not explicitly defined. The emission factors are usually stated in terms of the mass of pollutant emitted per vehicle and per unit distance (g vehicle^{-1} km^{-1}) or per unit of fuel consumed (g litre^{-1}).

Given their simplicity, aggregated emission factors are mainly applied on a large spatial scale, such as in national and regional emissions inventories, where little detailed information on vehicle operation is required. Aggregated emission factors for the regulated pollutants (CO, HC, NO_x and PM) and CO_2 are not generally used in detailed air pollution modelling exercises, as more sophisticated approaches are available. However, they are often the only means available for estimating emissions of unregulated pollutants, for which there is insufficient information to define a more detailed relationship with vehicle operation.

A number of aggregated emission factors are given in the European Environment Agency's COPERT model (Gkatzoflias *et al*., 2007). COPERT provides emission factors for the unregulated pollutants methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3) for urban, rural and motorway driving, and single emission factors which relate to all types of operation for heavy metals and specific organic compounds. The aggregated emission factors in COPERT are used in numerous national and regional emissions inventories. Aggregated emission factors have also been produced for unregulated pollutants in other projects.

2.2.2 Average-speed models

Average-speed functions are widely used to estimate hot exhaust emissions from road vehicles in regional and national inventories (including the NAEI), but are also incorporated into many local air pollution prediction models. Average-speed models are based upon the principle that the average emission factor for a certain pollutant and a given type of vehicle varies according to the average speed during a trip. The emission factor is again usually stated in grammes per vehicle-kilometre. Figure 1 shows how a continuous average-speed emission function is fitted to the emission factors measured for several vehicles over a range of driving cycles, with each cycle representing a specific type of driving, including stops, starts, accelerations and decelerations. The red line shows the fitted function and the blue points the underlying emission measurements.

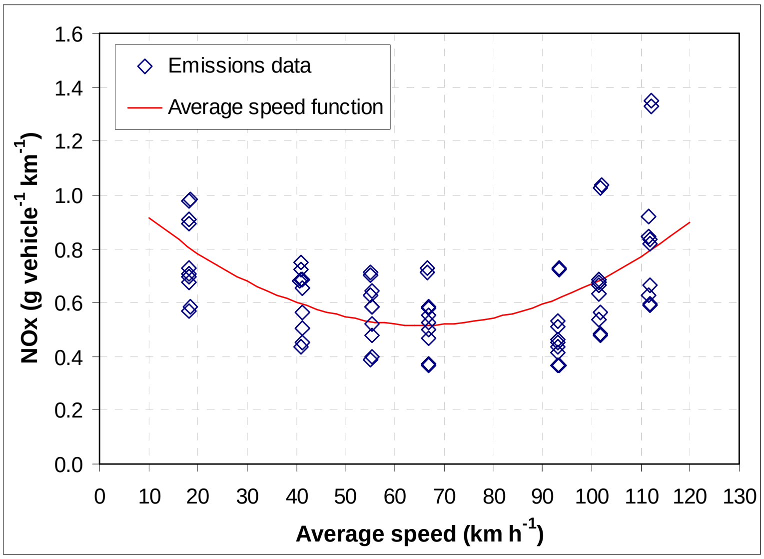

Figure 1: Average speed emission function for NO_x emissions from Euro 3 diesel cars <2.0 litres (Barlow *et al*., 2001).

Specific examples of average-speed models include the following:

MEET: The European Commission's 4th Framework project MEET (Methodologies for Estimating air pollutant Emissions from Transport) provided a basic Europe-wide procedure for evaluating the impact of transport on air pollutant emissions and energy consumption. The modes included were road transport, railways, water transport (inland and marine) and air transport. A variety of methods were used to calculate energy consumption and emissions, depending on the pollutant, the transport mode and the vehicle type (European Commission, 1999). The information from MEET has been used in a number of other models (see below).

COPERT: COPERT is a free program which can be used to calculate emissions of air pollutants from road transport, and contains some of the most widely used average-speed functions. The development of COPERT has been financed by the EEA as part of the activities of the European Topic Centre on Air and Climate Change. The initial version of the program, COPERT 85 (Eggleston *et al.*, 1989), was followed by COPERT 90 (Eggleston *et al.*, 1993), COPERT II (Ahlvik *et al.*, 1997) and COPERT III (Ntziachristos and Samaras, 2000). COPERT 4 (Gkatzoflias *et al.*, 2007)[8] is the latest update of the methodology. The current version draws its main principles and data from several European activities, including ARTEMIS and COST 346. COPERT 4 estimates emissions of all regulated air pollutants (CO, NO_x, VOC, PM) from different vehicle categories as a function of average speed. Functions are also provided for fuel consumption and unregulated pollutants.

ARTEMIS: The ARTEMIS[9] project commenced in 2000, and had two principal objectives. The first of these was to gain, through a programme of basic research, a better understanding of the causes of the differences in model predictions, and thus to address the uncertainties in emission modelling. One of the principal objectives of ARTEMIS was to develop a harmonised methodology for estimating emissions from all transport modes at the national and international levels. The software for the road transport model in ARTEMIS has been produced by INFRAS. It contains both emission factors for traffic situations and average-speed emission factors.

The NAEI model, which also uses average-speed functions, is described separately in Section 2.3.

A number of factors have contributed the widespread use of the average-speed approach. For example, it is one of the oldest approaches, the models are comparatively easy to use, a number of models are available free of charge, and there is a reasonably close correspondence between the required model inputs and the data generally available to users. In principle, the input is the trip-based average speed, although in practice it is also common for local speed measurements taken at discrete locations to be used. However, there are considered to be a number of limitations associated with average-speed models, including the following:

(i) Trips having very different vehicle operation[10] characteristics (and different emission levels) can have the same average speed. Clearly, all the types of operation associated with a given average speed cannot be accounted for by the use of a single emission factor. This is a particular problem at low-medium average speeds, for which the range of possible operational conditions associated with a given average speed is great.

(ii) In response to the tightening of emission control legislation, vehicles have been equipped with increasingly sophisticated after-treatment devices. For modern catalyst-equipped vehicles a large proportion of the total emission during a trip can be emitted as very short, sharp peaks, often occurring during gear changes and periods of high acceleration. Average speed has therefore become a less reliable indicator for the estimation of emissions for the newest generation of vehicles.

(iii) The shape of an average speed function is not fundamental, but depends on, amongst other factors, the types of cycle used in development of the functions. For example, each cycle used in the development of

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[8] http://lat.eng.auth.gr/copert/

[9] ARTEMIS: Assessment and Reliability of Transport Emission Models and Inventory Systems. A European Fifth Framework project. www.trl.co.uk/artemis/

[10] In this Report the term 'vehicle operation' refers to a wide range of parameters which describe the way in which a driver controls a vehicle (*e.g.* average speed, maximum speed, acceleration pattern, gear-change pattern), as well as the way in which the vehicle responds (*e.g.* engine speed, engine load).

the functions typically represents a given real-world driving condition, but the actual distribution of these driving conditions in the real world will vary by time and location.

(iv) Average speed models do not allow for detailed spatial resolution in emission predictions, and this is an important drawback in dispersion modelling.

The concept of ‘cycle dynamics’ has become useful for emission model developers to describe variations in vehicle operation for a given average speed (*e.g.* Sturm *et al*., 1998). In qualitative terms, cycle dynamics can be thought of as the ‘aggressiveness’ of driving, or the extent of ‘transient’[11] operation in a driving pattern. Quantitatively, the term refers to the variation in various properties or statistical descriptors of a vehicle operation pattern. As the information available to model users and developers has tended to be speed-based, interest has inevitably focussed on parameters which describe speed variation in some way. Some of the more useful parameters appear to be relative positive acceleration (Ericsson, 2000) and positive mean acceleration (Osses *et al*., 2002). However, most model users have little or no straightforward means of relating to descriptors of variation in vehicle operation, and several studies have also concluded that emissions should be described in terms of engine speed, load, power, and the changes in these parameters, not just variables relating to vehicle speed (Leung and Williams, 2000; Kean *et al*., 2003). Nevertheless, the concept is a useful one, especially when there is a need to discuss more advanced forms of modelling than the average-speed approach.

2.2.3 ‘Corrected’ average speed models

The TEE (Traffic Energy and Emissions) model (Negrenti, 1998) uses a ‘corrected average speed’ modelling approach. The model assumes that the effect of congestion on emissions at a certain average speed can be expressed by means of a ‘correction factor’ derived from average speed, green time percentage of traffic signals, link length and traffic density. The emission factor for the average speed is then adjusted using the correction factor. The congestion level is used to calculate the fractions of time spent during cruising, acceleration, deceleration and idling, and the end result is a reconstructed speed profile produced by the model itself. In fact, the TEE model uses emission factors from a simple instantaneous model (MODEM – see later) to calculate emissions for each of the phases, based on the reconstructed profile.

2.2.4 Traffic situation models

One approach for incorporating cycle dynamics in emission models involves the use of ‘traffic situations’. In traffic situation models, cycle average emission rates are correlated with various driving cycle parameters. These, in turn, are referenced to specific traffic situations which are known by the model user. Some traffic situations relate to conditions for which average speed may not be the best indicator of emissions. Traffic situation models tend to be best suited to local applications in which emission estimates are required for individual road links, but they can also be used for regional and national inventories.

The user must be able to relate to the way in which the traffic situations are defined. For example, the Handbook of Emission Factors (HBEFA) - used in Germany, Austria and Switzerland - is based on reference emission factors for different categories of vehicle. The latest version of HBEFA (version 2.1), was produced in February of 2004 (INFRAS, 2004). 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 speed variation (dynamics) variable is not quantified by the user but is defined by a textual description of the type of traffic situation to which an emission factor is applicable (*e.g.* ‘free-flow’, ‘stop and go’). However, asking the user to define the traffic situation using a textual description of speed variation or dynamics may lead to inconsistencies in interpretation. Furthermore, there are no universally accepted definitions for traffic situations. The model is designed specifically for use in the three countries mentioned, with the driving patterns for each traffic situation reflecting conditions in these countries. Its applicability to the UK is therefore questionable.

The traffic situation model developed in the ARTEMIS project is very similar to HBEFA, but the model is more widely applicable. The emission factors have been defined, but there are currently no default traffic statistics for the UK in the model.

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[11] In this context, the term ‘transient’ refers to a driving cycle in which the operation of the vehicle is continuously varying, as opposed to being in a steady state.

2.2.5 Multiple linear regression models

The VERSIT+ model (Smit *et al.*, 2005) employs a 'weighted-least-squares' multiple regression approach to the modelling of emissions, and is based on tests on a large number of cars over more than 50 different driving cycles. Within the model each driving cycle used is characterised by a large number of descriptive parameters (*e.g.* average speed, relative positive acceleration, number of stops per km) and their derivatives. For each pollutant and vehicle category (Euro 1 to Euro 4 cars) a regression model is fitted to the average emission values over the various driving cycles, resulting in the descriptive variables which are the best predictors of emissions (the group of descriptors being different in each case). A weighting is also applied to each emission value, based on the number of vehicles tested over each cycle and the inter-dependence of cycle variables. The VERSIT+ model requires a driving pattern as the input, from which it calculates the same range of descriptive variables and estimates emissions based on the regression results. The physical meaning of the variables may not necessarily be known. As with the other models requiring a driving pattern as the input, the use of the model will be restricted to a comparatively small number of users unless the inputs can be provided by, for example, a micro-simulation traffic model. VERSIT+ is not currently commercially available.

2.2.6 Instantaneous models

A number of detailed models aim to provide a precise description of vehicle emission behaviour by relating emission rates to vehicle operation during a series of short time steps (often one second). Several different terms have been used to describe such models, including 'modal', 'instantaneous', 'micro-scale', 'continuous' and 'on-line' (De Haan and Keller, 2000). In some models, vehicle operation is defined in terms of a relatively small number of modes - typically idle, acceleration, deceleration and cruise. For each of the modes the emission rate for a given vehicle category and pollutant is assumed to be fixed, and the total emission during a trip, or on a section of road, is calculated by weighting each modal emission rate by the time spent in the model (*e.g.* Hassounah and Miller, 1995; Hung *et al.*, 2005). Some instantaneous models, especially the older ones such as MODEM, relate fuel consumption and/or emissions to vehicle speed and acceleration during a driving cycle, typically at one-second intervals (*e.g.* Jost *et al.*, 1992; Hansen *et al.*, 1995). Other models, such as PHEM, use some description of the engine power requirement (Rexeis et al., 2005).

A number of instantaneous emission models were reviewed by Boulter *et al.* (2006). The level of detail involved in these models means that they are not suitable for use in national inventories, and they are better suited to local assessments.

2.3 The NAEI model

2.3.1 Model description

Details of the NAEI methodology are provided in the UK annual report of greenhouse gas emissions for submission under the Framework Convention on Climate Change (Choudrie *et al.*, 2008). The hot exhaust emission factors which are used for various categories of vehicle and pollutant are defined in the UK Emission Factor Database (UKEFD). During 2002, an updated version of the database, containing emission functions for CO, HC, NO_x, PM_{10}, benzene, 1,3-butadiene and CO_2, and functions describing fuel consumption, was prepared by TRL and NETCEN for use in the NAEI. The database included existing measurements from an earlier version, data from the EC MEET project, and a new set of measurements reported by TRL (Barlow *et al.*, 2001). With the exception of CO_2, the emission functions for the pollutants covered in the 2002 UKEFD were also identical to those given in the procedure for air pollution estimation in Volume 11 of the Design Manual For Roads and Bridges (DMRB), and are listed in Annex 5 of this same document (Highways Agency *et al.*, 2007)[12]. Volume 11 also describes the origins of the NAEI emission factors, which are also used in a number of other modelling tools, such as the Cambridge Environmental Research Consultants (CERC) air pollution prediction model ADMS[13].

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[12] The CO_2 emission factors in DMRB are currently being revised to tie in with the Government's transport analysis guidance tool web-TAG.

[13] http://www.cerc.co.uk/

For each vehicle category and pollutant, the average speed functions are expressed in the general form:

$$E = (a + b.v + c.v^2 + d.v^e + f.\ln(v) + g.v^3 + h/v + i/v^2 + j/v^3).x \qquad \text{(Equation 1)}$$

Where: E is the emission rate expressed in g km^{-1}
v is the average vehicle speed in km h^{-1}
a to j, and x are coefficients

The coefficients are provided in a spreadsheet[14]. Aggregated emission factors for other pollutants are provided on the NAEI web site.

2.3.2 Potential weaknesses in the NAEI emission factors

Recent UK and European Union (EU) research projects have identified potential weaknesses in the average-speed methodology used in the UK. There are also some areas of the NAEI's road transport model which are based on rather old data and are due to be updated. A number of specific weaknesses in the 2002 UKEFD were identified by Boulter *et al*. (2005b), 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.
    - There are no specific emission functions for taxis (in particular 'black cabs').
    - 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 included, with 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 gradient effects.
    - There are few emission measurements for very low and very high speeds, as well as for idling.

Gaps in the data will be addressed specifically in Task 3. It should also be noted that there is an absence of a detailed method for taking fuel properties ('fuel quality') into account. Furthermore, 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.

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[14] Available from http://www.naei.org.uk/data_warehouse.php

3 Model comparisons

In the first stage of the model assessment work, comparisons were made between the predictions of hot exhaust emissions from different types of model and the predictions obtained using the NAEI emission factors. The advantages and disadvantages of alternative models relative to the NAEI emission factors were noted. This work is adapted from that reported by Barlow and Boulter (2007).

3.1 Method

3.1.1 Model selection

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. As the NAEI contains the most commonly used emission factors in the UK, this was taken to represent the base case with which all other databases and models were compared. The models which were compared with the NAEI were:

- COPERT III[15] - 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 MODEM and PHEM were also included in the comparisons, although as stated earlier these types of model are not suitable for use in large-scale emission inventories. Table 2 shows the coverage of each model in terms of pollutants. The two instantaneous models only cover the regulated pollutants and CO_2. In fact, unregulated pollutants were excluded from the evaluation to reduce the overall complexity, and will be addressed separately in Task 3 of the project. In emission models hundreds of different vehicle categories are required to take account of the various factors affecting emissions. Table 3 shows the vehicle types covered by each model, and Table 4 to Table 7 show the legislative categories included.

Table 2: Pollutants included in the models
(✓=average speed/traffic situation/instantaneous, ●= aggregated emission factor, × = not covered).

Pollutant	Model (AS = average speed, TS = traffic situation, MLR = multiple linear regression)							
	NAEI (AS)	COPERT III (AS)	ARTEMIS V3b (AS)	ARTEMIS V3b (TS)	HBEFA V2.1 (TS)	VERSIT+ (MLR)	MODEM	PHEM
Regulated								
CO	✓	✓	✓	✓	✓	✓	✓	✓
THC/VOC	✓	✓	✓	✓	✓	✓	✓	✓
NO_x	✓	✓	✓	✓	✓	✓	✓	✓
PM	✓	✓	✓	✓	✓	✓	✓	✓
Unregulated								
CO_2 (measured)	×	×	✓	✓	×	✓	✓	×
CO_2 (ultimate)	✓	×	✓	✓	✓	×	×	×
Fuel consumption	✓	✓	✓	✓	✓	×	✓	✓
CH_4	×	✓/●	×	●	✓	×	×	×
Benzene	✓	●	×	●	✓	×	×	×
Toluene	×	×	×	●	✓	×	×	×
Xylene	×	×	×	●	✓	×	×	×
1,3-butadiene	✓	●	×	●	×	×	×	×
Other organic species	×	●	×	●	×	×	×	×
NO_2	×	×	×	×	×	×	×	×
N_2O	×	●	×	●	●	×	×	×
NH_3	×	●	×	●	●	×	×	×
PAH, POP	×	●	×	●	×	×	×	×
Dioxins, furans	×	●	×	×	×	×	×	×
SO_2	×	×	×	●	●	×	×	×
Lead	×	●	×	●	●	×	×	×
Other heavy metals	×	●	×	×	×	×	×	×

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[15] COPERT 4 was not available at the time this work was undertaken.

Table 3: Vehicle categories included in the models (✓= included, ✗ = not included).

Vehicle Category	Fuel	Engine size or maximum vehicle weight	Model							
			NAEI (AS)	COPERT III (AS)	ARTEMIS 3b (AS)	ARTEMIS 3b (TS)	HBEFA 2.1 (TS)	VERSIT+ (MLR)	MODEM	PHEM
Cars	Petrol	All	✗	✗	✗	✗	✗	✓	✗	✓
		<1.4 l	✓	✓	✓	✓	✓	✗	✓	✗
		1.4-2.0 l	✓	✓	✓	✓	✓	✗	✓	✗
		>2.0 l	✓	✓	✓	✓	✓	✗	✓	✗
	Petrol, DI	All	✗	✗	✓	✓	✗	✗	✗	✗
	Diesel	All	✗	✗	✗	✗	✗	✓	✗	✓
		<2.0 l	✓	✓	✓	✓	✓	✗	✓	✗
		>2.0 l	✓	✓	✓	✓	✓	✗	✓	✗
	CNG	All	✗	✗	✓	✓	✗	✗	✗	✗
	LPG	All	✗	✓	✓	✓	✗	✓	✗	✗
	Hybrid	(s/m/l)	✗	✗	✗	✓	✗	✗	✗	✗
LGV	Petrol	All	✓	✓	✗	✗	✓	✗	✗	✗
		M+N1-I	✗	✗	✓	✓	✗	✗	✗	✗
		M+N1-II	✗	✗	✓	✓	✗	✗	✗	✗
		M+N1-III	✗	✗	✓	✓	✗	✗	✗	✗
	Diesel	All	✓	✓	✗	✗	✓	✗	✗	✗
		M+N1-I	✗	✗	✓	✓	✗	✗	✗	✗
		M+N1-II	✗	✗	✓	✓	✗	✗	✗	✗
		M+N1-III	✗	✗	✓	✓	✗	✗	✗	✗
	CNG/petro	All	✗	✗	✓	✓	✗	✗	✗	✗
HGV	Petrol	All	✗	✓	✓	✓	✓	✗	✗	✓
	Diesel	Rigid, all	✓	✗	✗	✗	✗	✗	✗	✗
		Rigid, <=7.5t	✗	✓	✓	✓	✓	✗	✗	✓
		Rigid, 7.5-12t	✗	✗	✓	✓	✓	✗	✗	✓
		Rigid, 7.5-16t	✗	✓	✗	✗	✗	✗	✗	✗
		Rigid, >12-	✗	✗	✓	✓	✓	✗	✗	✓
		Rigid, >14-	✗	✗	✓	✓	✓	✗	✗	✓
		Rigid, >16-	✗	✓	✗	✗	✗	✗	✗	✗
		Rigid, >20-	✗	✗	✓	✓	✓	✗	✗	✓
		Rigid, >26-	✗	✗	✓	✓	✓	✗	✗	✓
		Rigid, >28-	✗	✗	✓	✓	✗	✗	✗	✓
		Rigid, >32t	✗	✓	✓	✓	✗	✗	✗	✓
		Artic, all	✓	✗	✗	✗	✗	✗	✗	✗
		Artic, <=7.5t	✗	✓	✓	✓	✗	✗	✗	✓
		Artic, >7.5-	✗	✗	✓	✓	✗	✗	✗	✓
		Artic, >7.5-	✗	✓	✗	✗	✗	✗	✗	✗
		Artic, >14-20t	✗	✗	✓	✓	✗	✗	✗	✓
		Artic, >20-28t	✗	✗	✓	✓	✓	✗	✗	✓
		Artic, >28-34t	✗	✗	✓	✓	✓	✗	✗	✓
		Artic, >32t	✗	✓	✗	✗	✗	✗	✗	
		Artic, >34-40t	✗	✗	✓	✓	✓	✗	✗	✓
		Artic, >40-50t	✗	✗	✓	✓	✗	✗	✗	✓
		Artic, >50-60t	✗	✗	✓	✓	✗	✗	✗	✓
	CNG	Rigid, all	✗	✗	✓	✓	✗	✗	✗	✓
Urban bus	Diesel	All	✓	✓	✗	✗	✗	✗	✗	✗
		<15t	✗	✗	✓	✓	✓	✗	✗	✓
		>15-18t	✗	✗	✓	✓	✓	✗	✗	✓
		>18t	✗	✗	✓	✓	✓	✗	✗	✓
	CNG	<15t	✗	✗	✓	✓	✗	✗	✗	✓
		>15-18t	✗	✗	✓	✓	✗	✗	✗	✓
		>18t	✗	✗	✓	✓	✗	✗	✗	✓
	Ethanol	>15-18t	✗	✗	✓	✓	✗	✗	✗	✓
		>18t	✗	✗	✓	✓	✗	✗	✗	✓
Coach	Diesel	All	✓	✓	✗	✗	✗	✗	✗	✗
		<15t	✗	✗	✓	✓	✓	✗	✗	✓
		>15-18t	✗	✗	✓	✓	✓	✗	✗	✓
		>18t	✗	✗	✓	✓	✓	✗	✗	✓
	CNG	<15t	✗	✗	✓	✓	✗	✗	✗	✓
		>15-18t	✗	✗	✓	✓	✗	✗	✗	✓
		>18t	✗	✗	✓	✓	✗	✗	✗	✓
M'cycles*	Petrol	Moped <=50cc	✓	✓	✓	✓	✗	✗	✗	✗
		2-S >50cc	✗	✓	✗	✗	✗	✗	✗	✗
		2-S <=150cc	✗	✗	✓	✓	✓	✗	✗	✗
		2-S >150cc	✗	✗	✓	✓	✓	✗	✗	✗
		2-S <250cc	✓	✗	✗	✗	✗	✗	✗	✗
		4-S <=150cc	✗	✗	✓	✓	✓	✗	✗	✗
		4-S 50-250cc	✗	✓	✗	✗	✗	✗	✗	✗
		4-S 150-250cc	✗	✗	✓	✓	✓	✗	✗	✗
		4-S <250cc	✓	✗	✗	✗	✗	✗	✗	✗
		4-S 250-750cc	✓	✓	✓	✓	✓	✗	✗	✗
		4-S >750cc	✓	✓	✓	✓	✓	✗	✗	✗

* '2-S' = two-stroke; '4-S' = four-stroke.

Table 4: Legislative categories included in the models - cars (✓= included, × = not included).

Vehicle class	Fuel	Emission legislation	Model							
			NAEI (AS)	COPERT III (AS)	ARTEMIS 3b (AS)	ARTEMIS 3b (TS)	HBEFA 2.1 (TS)	VERSIT+ (MLR)	MODEM	PHEM
Cars	Petrol	ECE 15.03	✓	✓	✓	✓	✓	×	×	×
		ECE 15.04	✓	✓	✓	✓	✓	×	×	×
		All pre-Euro 1	×	×	×	×	×	×	✓	✓
		Euro 1	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 2	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 3	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 4	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 5	×	×	✓	✓	×	×	×	×
	Petrol,	Euro 4	×	×	✓	✓	×	×	×	×
		Euro 5	×	×	✓	✓	×	×	×	×
	Diesel	All pre-Euro 1	✓	✓	✓	✓	✓	×	✓	✓
		Euro 1	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 2	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 3	✓	✓	✓	✓	✓	✓	✓	✓
		Euro 3 + PM	✓	×[a]	×[a]	×[a]	×	×	×	×
		Euro 4	✓	✓	×	✓	✓	✓	✓	✓
		Euro 4 + PM	✓	×[a]	×[a]	×[a]	×	✓	×	×
		Euro 5	×	×	×	✓	×	×	×	×
	LPG	All pre-Euro 1	×	✓	✓	✓	×	×	×	×
		Euro 1	×	✓	✓	✓	×	✓	×	×
		Euro 2	×	✓	✓	✓	×	✓	×	×
		Euro 3	×	✓	✓	✓	×	✓	×	×
		Euro 4	×	✓	✓	✓	×	✓	×	×
		Euro 5	×	✓	✓	✓	×	×	×	×
	CNG	Euro 2	×	×	✓	✓	×	×	×	×
		Euro 3	×	×	✓	✓	×	×	×	×
		Euro 4	×	×	✓	✓	×	×	×	×
		Euro 5	×	×	✓	✓	×	×	×	×
	Hybrid	Euro 4	×	×	×	✓	×	×	×	×

[a] ARTEMIS model has correction for PM filter.

Table 5: Legislative categories included in the models - LGVs (✓= included, × = not included).

Vehicle class	Fuel	Emission legislation	Model							
			NAEI (AS)	COPERT III (AS)	ARTEMIS 3b (AS)	ARTEMIS 3b (TS)	HBEFA 2.1 (TS)	VERSIT+ (MLR)	MODEM	PHEM
LGV	Petrol	All pre-Euro 1	✓	✓	×	✓	✓	×	×	×
		Euro 1	✓	✓	×	✓	✓	×	×	×
		Euro 2	✓	✓	×	✓	✓	×	×	×
		Euro 3	✓	✓	×	✓	✓	×	×	×
		Euro 4	✓	✓	×	✓	✓	×	×	×
		Euro 5	×	×	×	✓	×	×	×	×
	Diesel	All pre-Euro 1	✓	✓	×	✓	✓	×	×	×
		Euro 1	✓	✓	×	✓	✓	×	×	×
		Euro 2	✓	✓	×	✓	✓	×	×	×
		Euro 3	✓	✓	×	✓	✓	×	×	×
		Euro 4	✓	✓	×	✓	×	×	×	×
		Euro 5	×	×	×	✓	×	×	×	×
	CNG	Euro 2	×	×	×	✓	×	×	×	×
		Euro 3	×	×	×	✓	×	×	×	×
		Euro 4	×	×	✓	✓	×	×	×	×

Table 6: Legislative categories included in the models HGVs, buses and coaches (✓= included, × = not included).

Vehicle class	Fuel	Emission legislation	Model							
			NAEI (AS)	COPERT III (AS)	ARTEMIS 3b (AS)	ARTEMIS 3b (TS)	HBEFA 2.1 (TS)	VERSIT+ (MLR)	MODEM	PHEM
HGV	Petrol	Conventional	×	✓	✓	✓	✓	×	×	×
	Diesel	All pre-Euro I	✓	✓	✓	✓	✓	×	×	✓
		Euro I	✓	✓	✓	✓	✓	×	×	✓
		Euro II	✓	✓	✓	✓	✓	×	×	✓
		Euro III	✓	✓	✓	✓	✓	×	×	✓
		Euro IV	✓	✓	✓	✓	✓	×	×	✓
		Euro V	✓	✓	✓	✓	×	×	×	✓
	CNG	Euro II	×	×	✓	✓	×	×	×	✓
		Euro III	×	×	✓	✓	×	×	×	✓
		Euro IV	×	×	✓	✓	×	×	×	✓
Urban bus/coach	Diesel	All pre-Euro I	✓	✓	✓	✓	✓	×	×	✓
		Euro I	✓	✓	✓	✓	✓	×	×	✓
		Euro II	✓	✓	✓	✓	✓	×	×	✓
		Euro III	✓	✓	✓	✓	✓	×	×	✓
		Euro IV	✓	✓	✓	✓	✓	×	×	✓
		Euro V	✓	✓	✓	✓	×	×	×	✓
	CNG	Euro II	×	×	✓	✓	×	×	×	✓
		Euro III	×	×	✓	✓	×	×	×	✓
		Euro IV	×	×	✓	✓	×	×	×	✓

Table 7: Legislative categories[16] included in the models - motorcycles (✓= included, × = not included).

Vehicle class	Fuel	Emission legislation	Model							
			NAEI (AS)	COPERT III (AS)	ARTEMIS 3b (AS)	ARTEMIS 3b (TS)	HBEFA 2.1 (TS)	VERSIT+ (MLR)	MODEM	PHEM
Motorcycles	Petrol	Pre-Euro 1	✓	✓	✓	✓	✓	×	×	×
		Euro 1	✓	✓	✓	✓	✓	×	×	×
		Euro 2	×	×	✓	✓	✓	×	×	×
		Euro 3	×	×	✓	✓	×	×	×	×

The models use slightly different vehicle categories and have different levels of detail. For example, the classification in the ARTEMIS models is generally more detailed than that in the NAEI. It should also be noted that although some of the broader vehicle categories are stated as not being covered by some emission models (*e.g.* all petrol cars in the NAEI average speed model), weighted functions can be derived using an appropriate fleet model. In terms of the different categories of emission legislation, ARTEMIS again offers more detail than the NAEI.

3.1.2 Definition of driving patterns

The second stage of the evaluation process involved the definition of a series of vehicle operating profiles (driving patterns) to be used as the input to the various models. TRL has collected a large database of real-world driving patterns using instrumented vehicles as part of several research projects. These research projects are summarised in Table 8. The earlier measurements involved the installation of various transducers and data loggers in the test vehicles. The more recent measurements were obtained directly via the vehicle OBD (on-board diagnostics) or CAN (controlled area network) interfaces, with GPS (global positioning system) being used to generate location data.

The total number of trips, distance driven and hours of driving are given by project and vehicle category in Table 9, Table 10 and Table 11. Most of the driving patterns were for cars, and there was only a limited amount of data for LGVs, HGVs and buses. For LGVs and buses, the data were taken from a single project (UG214), which dealt with traffic management in urban and suburban areas (with relatively slow speeds). The HGV data

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[16] Although the nomenclature for the motorcycle legislation is the same as that used for light-duty vehicles, the legislation itself (procedure, limit values, *etc.*) is different. The limits for Euro 1 vehicles are given in Directive 97/24/EC Chapter 5, and those for Euro 2 and 3 vehicles are contained in Directive 2002/51/EC.

were also taken from the UG214 project, but were supplemented with measurements collected during another project (M42) dealing with motorway driving.

The full database contained slightly less than 5,000 driving patterns, which covered more than 73,000 kilometres and had a total duration of almost 1,750 hours. As the use of so much data as model input would take a considerable amount of time, a representative sub-sample of driving patterns was selected for each vehicle category. The driving patterns were selected from within various bands of speed and positive acceleration, and covered the ranges of these parameters in the full database.

Table 8: Research projects involving the measurement of real-world driving patterns.

Project (customer)	Year(s)	Project description	Location(s)	Road type(s)
AVERT (DfT)	2002	The effects of driving style on exhaust emissions and fuel consumption.	Southampton	Urban and suburban
UG106 (DfT)	1996-2001	Evaluation of Safer City Project, with annual measurements along set routes over 6 years.	Gloucester	Urban and suburban
UG93 (DfT)	1997-1998	Evaluation of traffic management and traffic calming schemes.	Havant	Residential with traffic calming
HOV Lane (HA)	2000	Logging along the A2/A102 prior to the introduction of a high-occupancy lane (not implemented).	A2/A102 M25-Blackwall	Trunk
M25 VSL (HA)	2000-2001	Evaluation of variable speed limit pilot scheme and extension.	M25	Motorway
M42 (HA)	2003-2004	Evaluation of active traffic management scheme.	M42, Birmingham	Motorway
M6 (HA)	2000	Pre-scheme logging prior to proposed new speed limits (not implemented).	M6, Birmingham	Motorway
OSCAR (EC, DfT)	2003	Evaluation of air quality dispersion models.	Central London	City centre
UG214 (DfT)	2000-2001	Development of driving cycles for various vehicle categories and traffic management schemes.	Kingston, Richmond, S'ampton, Havant, Oxford, Gloucester, Reading	Urban with traffic management
UG127 (DfT)	1997-1999	Evaluation of the effects of traffic calming on exhaust emissions.	Bracknell, Harrow, Sandhurst, Slough, Sutton, Walton-on-Thames.	Residential with traffic calming
WSL cycles (DfT)	1995	Development of the Warren Spring Laboratory driving cycles.	Stevenage, Hitchin, A1(M)	Urban, suburban, rural, motorway

Table 9: Driving patterns from TRL research projects – number of trips.

Project	Number of trips				
	Buses	Cars	HGVs	LGVs	Total
AVERT		10			10
UG106		1,433			1,433
UG93		258			258
HOV Lane		24			24
M25 VSL		809			809
M42		346	203		549
M6		242			242
OSCAR		45			45
UG214	225	225	223	367	1,040
UG127		18			18
WSL cycles		557			557
Grand total	225	3,967	426	367	4,985

Table 10: Driving patterns from TRL research projects – distance driven.

Project	Total distance driven (km)				
	Buses	Cars	HGVs	LGVs	Total
AVERT		187			187
UG106		14,504			14,504
UG93		2,767			2,767
HOV Lane		1,188			1,188
M25 VSL		16,933			16,933
M42		11,561	7,426		18,987
M6		3,652			3,652
OSCAR		364			364
UG214	2,349	1,993	1,800	4,077	10,219
UG127		107			107
WSL cycles		4,276			4,276
Grand total	2,349	57,532	9,226	4,077	73,184

Table 11: Driving patterns from TRL research projects – duration.

Project	Total duration (hours)				
	Buses	Cars	HGVs	LGVs	Total
AVERT		6.0			6.0
UG106		459.0			459.0
UG93		80.5			80.5
HOV Lane		22.5			22.5
M25 VSL		270.8			270.8
M42		164.4	117.4		281.7
M6		65.5			65.5
OSCAR		27.6			27.6
UG214	110.3	76.3	98.7	159.0	444.4
UG127		2.7			2.7
WSL cycles		88.2			88.2
Grand total	110.3	1,263.7	216.1	159.0	1,749.1

The numbers of driving patterns in the sub-samples for the different vehicle categories are listed in Table 12. The average speed and average positive acceleration values for both the driving patterns in the full database and those in the sub-samples are shown in Figure 2, Figure 3, Figure 4 and Figure 5 for cars, LGVs, HGVs and buses respectively. The driving patterns for cars and HGVs covered a wide range of average speed. However, the average speeds of the driving patterns for LGVs and buses were concentrated at the lower end of the speed range due to data only being collected in urban areas. This would be expected for buses as they operate principally in urban areas. However, LGVs are used on all types of road and in all types of area, and consequently the range of real-world operation was not fully represented in the TRL database.

Table 12: Numbers of driving patterns in sub-samples.

Vehicle Category	Number of driving patterns
Cars	122
LGVs	110
HGVs	120
Buses	115

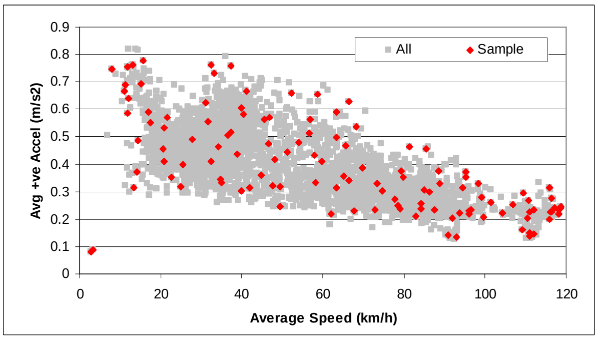


Figure 2: Average speed and positive acceleration of driving patterns - cars.

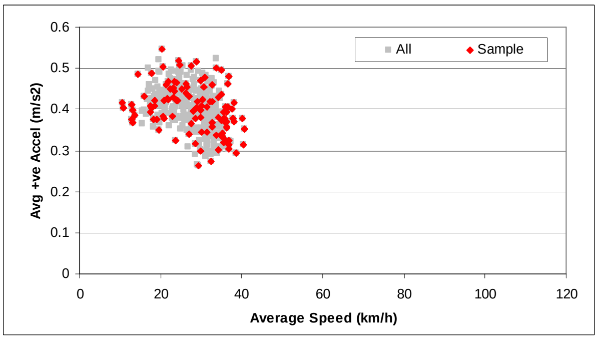


Figure 3: Average speed and positive acceleration of driving patterns - LGVs.

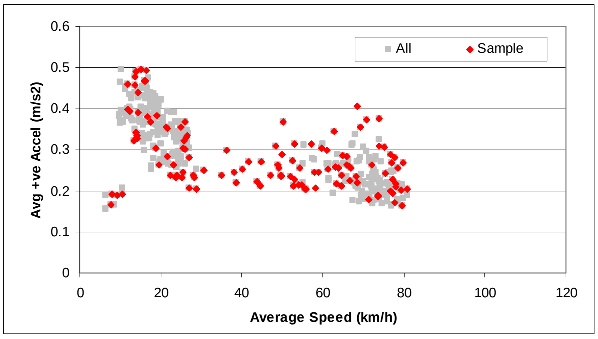


Figure 4: Average speed and positive acceleration of driving patterns - HGVs.

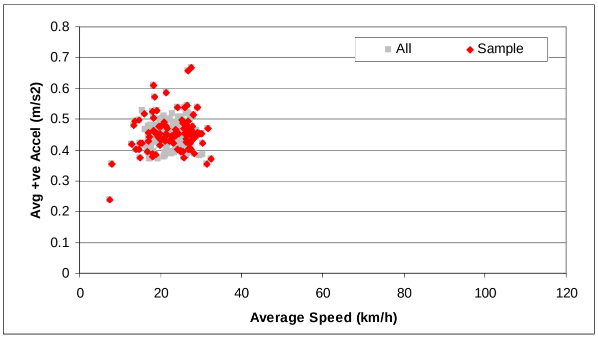


Figure 5: Average speed and positive acceleration of driving patterns - buses.

3.1.3 Model execution and evaluation

Each driving pattern was processed using all the models included in the evaluation, and emission factors were determined for the specified vehicle categories (*e.g.* petrol cars, diesel cars, petrol LGVs, diesel LGVs, different engine size ranges, different levels of emission legislation). The outputs from the different models were then compared - on the basis of a number of statistical parameters - with the emission factors currently used in the NAEI/DMRB (referred to hereafter as NAEI). As an example, Figure 6 shows a comparison between model estimates (in this case HBEFA, which has emissions at specific vehicle speeds only) and the estimates from NAEI (which uses a continuous function). In order to calculate the various statistical parameters, it is first necessary to recalculate the NAEI emissions at the corresponding speeds, as shown in Figure 7.

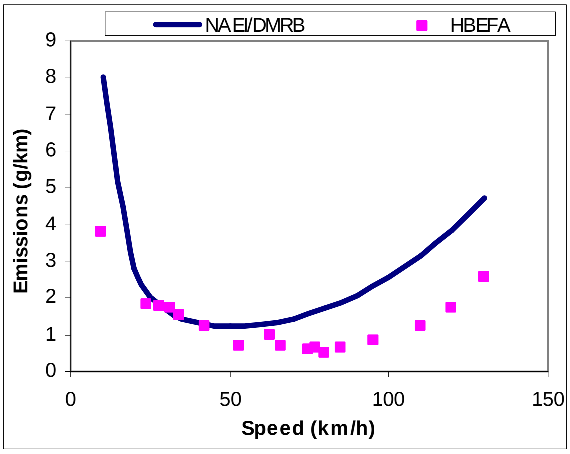


Figure 6. Explicit emission estimates compared with a continuous function

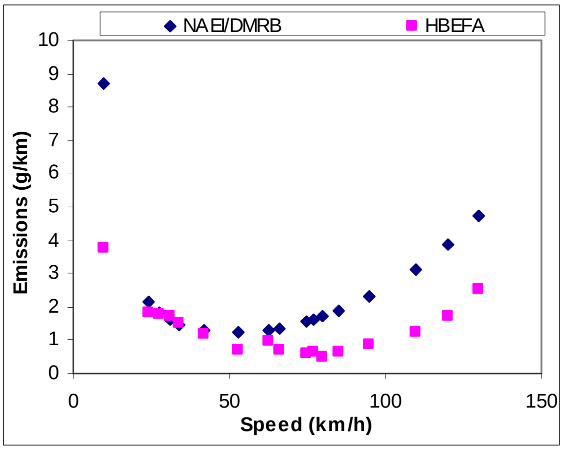


Figure 7. Corresponding equivalent values from continuous function

These data are also shown in Table 13. Column *a* (Estimate 1) is the base case emission (*i.e.* NAEI) and column *b* (Estimate 2) shows the data being compared with it (from HBEFA in this example). Column *c* gives the difference between the two, and column *d* shows the absolute difference. From these data the following parameters were calculated:

Sample size: This was simply the number of emission estimates in the sample.

Average difference: This was the average of all the differences (bottom row of column ‘c’ in Table 13).

Std Dev of differences: The standard deviation of the differences (column ‘c’). The standard deviation is a measure of how widely values are dispersed around the average value.

RMS error: The root mean square (RMS) error is a method of measuring errors (*i.e.* the differences between the emission estimates) without positive and negative errors cancelling one another out. This was calculated by squaring all the errors, summing them, dividing by the number of samples and then taking the square root. An example calculation is shown in Table 14.

Maximum difference: This is the maximum absolute difference and the speed at which is occurs. In the sample shown in Table 13 the largest absolute difference is 4.9131, which occurs at a speed of 9.5 km h^{-1}. This statistic shows where on the speed curve the maximum discrepancies are occurring. However, it should be noted that this could be due to an outlier rather than the general trend of the two samples.

Minimum difference @ speed: This is the minimum absolute difference and the speed at which it occurs. In the example above this is 0.0327, and occurs at 34 km h^{-1}. This shows where on the curve the closest agreement occurs, though again this could be due to an outlier rather than the general trend.

t-value and probability: The *t* value and probability test the hypothesis that the average difference is zero, low probabilities suggest this is not likely to be true. The *t* value is calculated by dividing the average difference by the standard deviation of the differences.

Correlation: The correlation shows whether the curves are similar shapes or not. This is the *r* value. A value of +1 would indicate that the curves are identical in shape. A value of -1 would indicate that the curves are mirror images of one another. Values close to zero would indicate no similarity at all between the two curves. However, if the shapes of the curves are correct, they could be off-set from one another and still give a high correlation.

The calculated statistical parameters for the above example are listed in Table 15. For the different pollutants and vehicle types the magnitude of the average differences and RMS errors vary according to the magnitude of the emissions - *e.g.* for one vehicle class, the RMS error for CO is 0.758 but for CO_2 it is 363.1. These have therefore been related to an average emission value to give a relative measure of the discrepancy. A number of different emission magnitudes were examined, including average, median and mid-range emissions. However, in following analysis the average of the emissions between 30 and 90 km h^{-1} has been used as the emissions magnitude. This range avoids possible errors occurring at both speed extremes (very low speed and very high speed) and should be applicable to all vehicle types. The relative values are included in Table 15 with an example of the emissions magnitude used to calculate the relative values shown in Table 16.

In order to illustrate the effects of the statistical parameters described above, four different types of curve fit are illustrated in Figure 9 – ranging from very good to very bad. These are shown graphically (plotted against speed) and in terms of the resulting statistical parameters.

- The first example has a very high correlation (0.99), a low relative average difference (2.3%) and a low relative RMS error (18.57%). The graph shows how good the comparison is.
- The second example has a fairly high correlation (0.88), a poor relative difference (269%) and a poor relative RMS error (319%), showing that the curve shape is quite good but is displaced – *i.e.* the HBEFA emissions are higher than the NAEI ones.
- The third example has a reasonable correlation (0.63), a very poor relative difference (883%) and a very poor relative RMS error (1059%), showing that the curve shape has a reasonable agreement with the NAEI, but is displaced and does not intersect the data points.
- The fourth example has a negative correlation (-0.383), a low relative difference (-23.24%) and a low relative RMS error (70.98%), showing how poor the curve is (the trends are almost opposite) although the curve goes through the middle of the data points.

Table 13. Example comparison of two emissions estimates.

	a	*b*	*c*	*d*
Speed (km h^{-1})	Estimate 1 (g km^{-1})	Estimate 2 (g km^{-1})	Difference *(b-a)*	Absolute difference *Abs(c)*e
130.00	4.7114	2.5401	-2.1713	2.1713
85.00	1.8737	0.6318	-1.2419	1.2419
120.00	3.8582	1.7413	-2.1169	2.1169
110.00	3.1402	1.2410	-1.8992	1.8992
95.00	2.2954	0.8451	-1.4503	1.4503
80.00	1.7026	0.5006	-1.2019	1.2019
74.91	1.5545	0.5841	-0.9704	0.9704
9.50	8.6929	3.7798	-4.9131	4.9131
77.00	1.6121	0.6291	-0.9830	0.9830
66.00	1.3577	0.7060	-0.6517	0.6517
62.60	1.3037	0.9770	-0.3268	0.3268
53.10	1.2191	0.6996	-0.5195	0.5195
42.10	1.2703	1.2068	-0.0635	0.0635
31.10	1.6013	1.7139	0.1126	0.1126
34.00	1.4714	1.5042	0.0327	0.0327
27.67	1.8186	1.7718	-0.0469	0.0469
24.13	2.1511	1.8314	-0.3197	0.3197
Average	2.4491	1.3473	-1.1018	1.1189

Table 14. Example RMS error calculation

e	e^2
-2.1713	4.7144
-1.2419	1.5423
-2.1169	4.4814
-1.8992	3.6071
-1.4503	2.1033
-1.2019	1.4446
-0.9704	0.9417
-4.9131	24.1383
-0.9830	0.9662
-0.6517	0.4247
-0.3268	0.1068
-0.5195	0.2699
-0.0635	0.0040
0.1126	0.0127
0.0327	0.0011
-0.0469	0.0022
-0.3197	0.1022
Sum(e^2)	44.8629
n	17
Sum(e^2)/n	2.6390
Sqrt(Sum(e^2)/n)	1.6245

Table 15. Calculated statistics

Parameter	Actual value	Relative to Estimate 1 average
Sample size	17	
Average difference	-1.1018	-72.33%
Std Dev of differences	1.2305	80.78%
RMS error	1.6245	106.65%
Max difference	4.9131	322.54%
@ speed (km h^{-1})	9.5	
Min difference	0.0327	2.15%
@ speed (km h^{-1})	34	
t-value	-0.8954	
Probability	0.3847	
Correlation	0.8566	

Table 16. Average emissions 30-90 km h^{-1}

Speed (km h^{-1})	Estimate 1 (g km^{-1})
30	1.6623
40	1.3050
50	1.2149
60	1.2706
70	1.4362
80	1.7026
90	2.0711
Average	1.5232

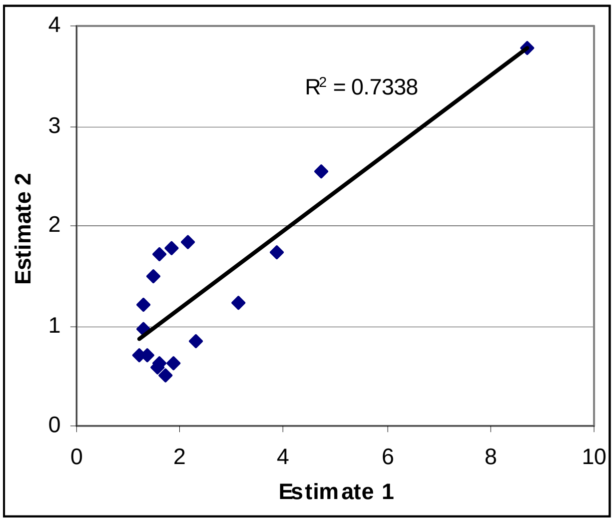
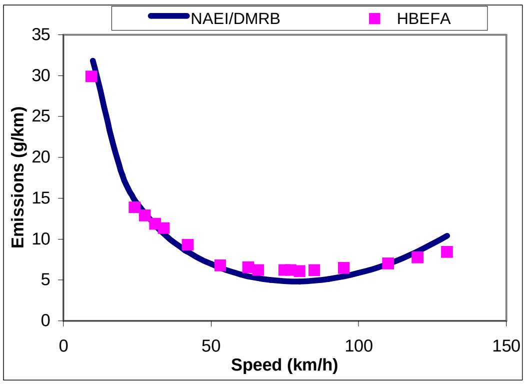
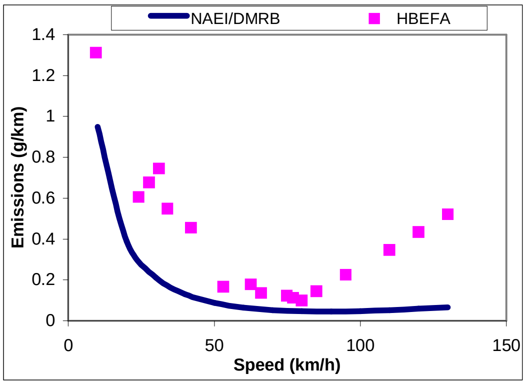


Figure 8. Correlation between the two estimates.

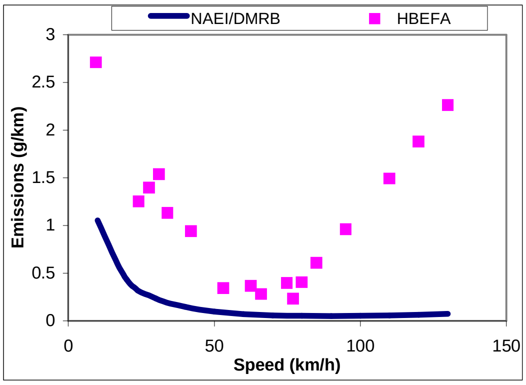
Parameter	**Actual value**	**Relative to NAEI/DMRB average**
Sample size	17	
Average difference	0.1600	2.30%
Std Dev of differences	1.3225	18.99%
RMS error	1.2929	18.57%
Max difference	3.3582	48.23%
@ speed (km/h)	9.5	
Min difference	0.0423	0.61%
@ speed (km/h)	110	
t-value	0.1210	
Probability	0.9053	
Correlation	0.9932	
Avg NAEI/DMRB$_{30-90}$	6.9624	



Parameter	**Actual value**	**Relative to NAEI/DMRB average**
Sample size	17	
Average difference	0.2458	268.77%
Std Dev of differences	0.1612	176.25%
RMS error	0.2913	318.55%
Max difference	0.5443	595.18%
@ speed (km/h)	31.10000038	
Min difference	0.0524	57.25%
@ speed (km/h)	80	
t-value	1.5250	
Probability	0.1481	
Correlation	0.8755	
Avg NAEI/DMRB$_{30-90}$	0.0915	



Parameter	**Actual value**	**Relative to NAEI/DMRB average**
Sample size	17	
Average difference	0.8973	883.09%
Std Dev of differences	0.6115	601.85%
RMS error	1.0757	1058.66%
Max difference	2.1901	2155.41%
@ speed (km/h)	130	
Min difference	0.1783	175.48%
@ speed (km/h)	77	
t-value	1.4673	
Probability	0.1630	
Correlation	0.6317	
Avg NAEI/DMRB$_{30-90}$	0.1016	



Parameter	**Actual value**	**Relative to NAEI/DMRB average**
Sample size	17	
Average difference	-0.1385	-23.24%
Std Dev of differences	0.4119	69.13%
RMS error	0.4229	70.98%
Max difference	0.9322	156.45%
@ speed (km/h)	9.5	
Min difference	0.0098	1.65%
@ speed (km/h)	80	
t-value	-0.3362	
Probability	0.7414	
Correlation	-0.3830	
Avg NAEI/DMRB$_{30-90}$	0.5959	

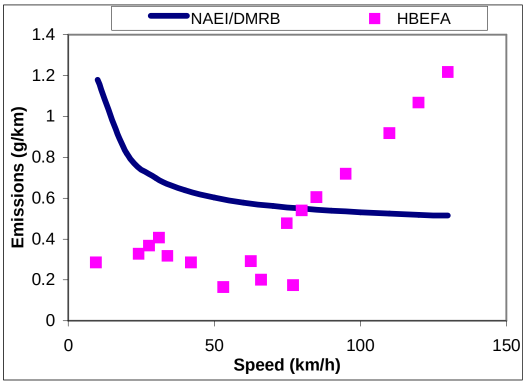


Figure 9. Example comparisons, showing how the quality of the fit effects the statistical parameters.

3.2 Results

Each driving pattern was processed using all the models, and emission factors for the regulated pollutants (CO, THC, NO_x, PM) and CO_2 were determined for the relevant vehicle categories (*e.g.* petrol cars, diesel cars, petrol and diesel LGVs, HGVs, buses, different engine size ranges, different levels of emission legislation). The results were then compared with the emission factors contained within the NAEI.

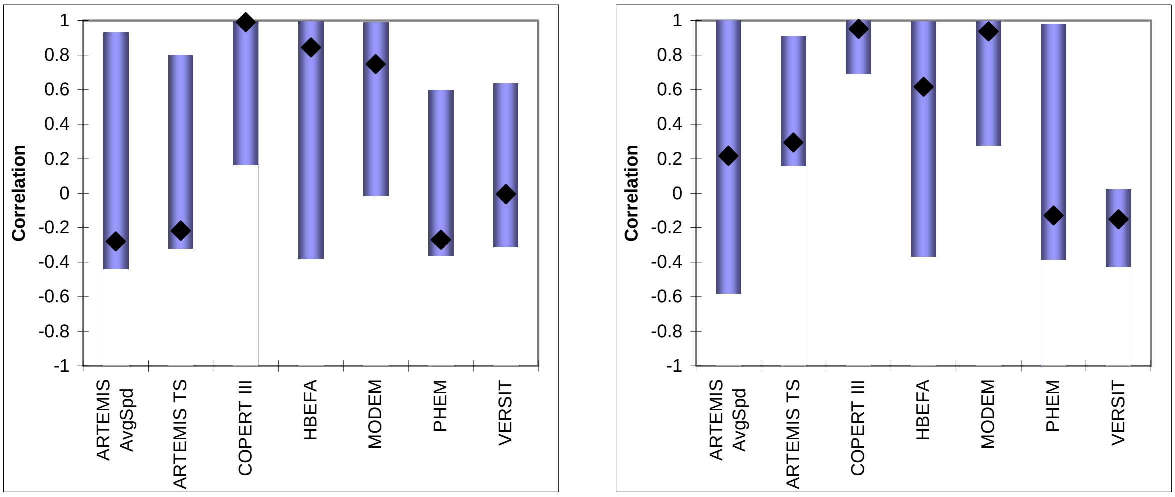
An extremely large amount of data was generated. In order to simplify the presentation of the results, the data were sorted into six groups:

(i) Petrol cars
(ii) Diesel cars
(iii) Petrol and diesel LGVs
(iv) Diesel HGVs
(v) Diesel buses
(vi) Motorcycles (including mopeds)

For each group, the relevant data were extracted and the range and median values were determined. The following graphs show the ranges and median values:

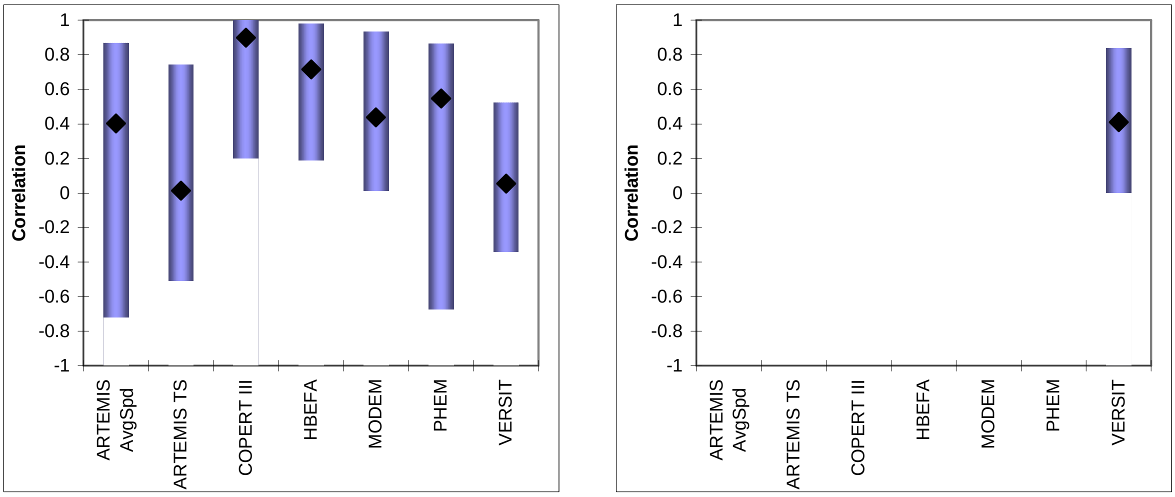
- Figure 10 and Figure 11: correlation and relative RMS for petrol cars respectively
- Figure 12 and Figure 13: correlation and relative RMS for diesel cars respectively
- Figure 14 and Figure 15: correlation and relative RMS for petrol and diesel LGVs respectively
- Figure 16 and Figure 17: correlation and relative RMS for diesel HGVs respectively
- Figure 18 and Figure 19: correlation and relative RMS for diesel buses respectively
- Figure 20 and Figure 21: correlation and relative RMS for motorcycles respectively

Each Figure contains the comparisons for CO, HC, NO_x, PM and CO_2. In all cases emissions from the various models have been compared with the NAEI. It should be noted that these values simply indicate similarities or differences with the NAEI and do not indicate whether the emission estimates are accurate. Nevertheless, similarities in the predictions of different models would tend to improve the confidence with which the emission factors may be viewed, although it should be noted that there is considerable sharing of data between the emission models in use in Europe.



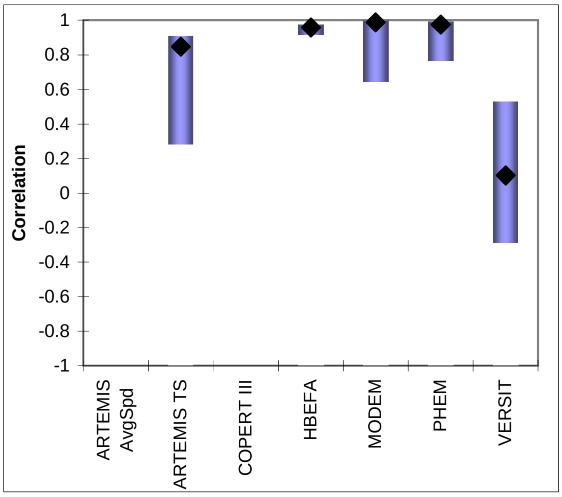
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



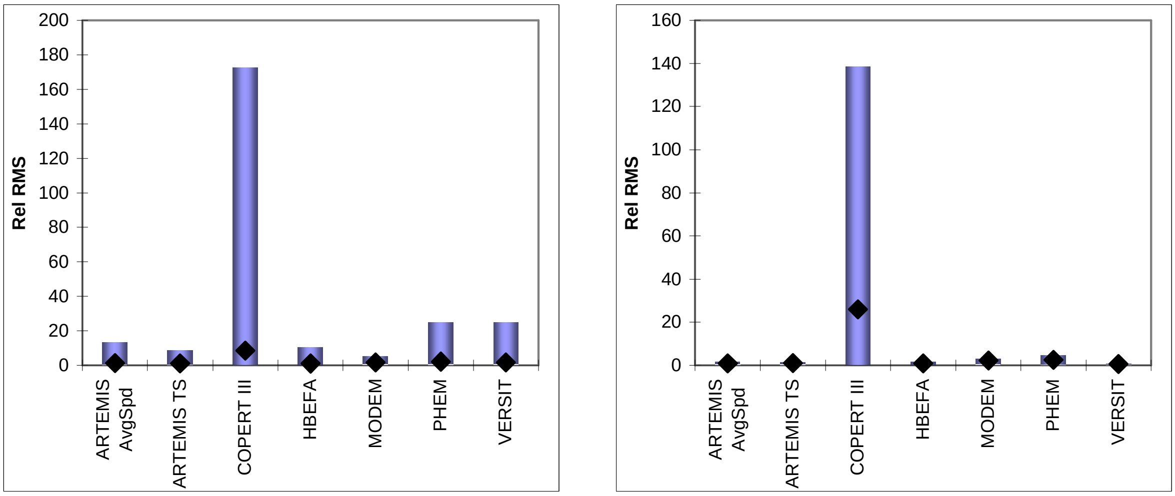
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



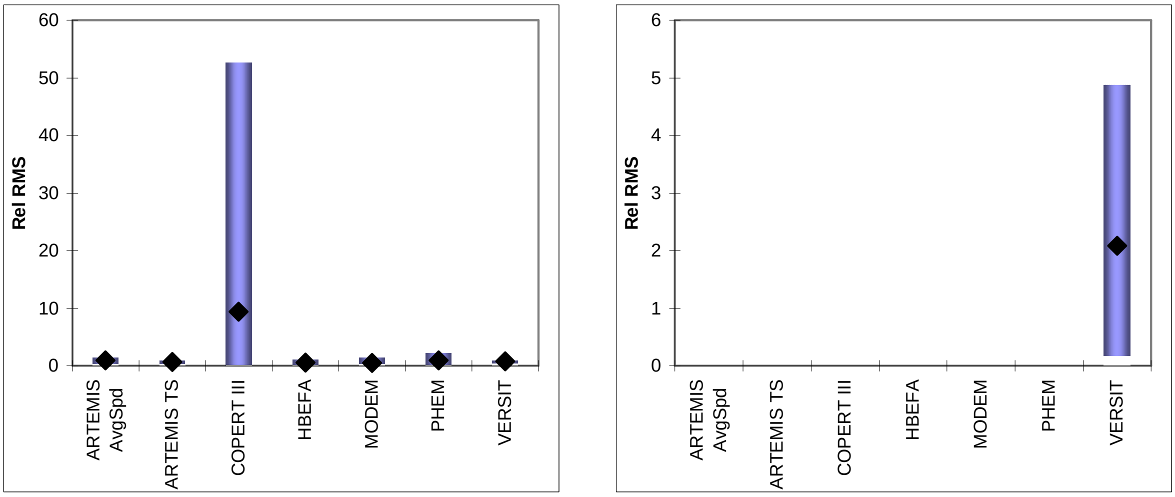
e. Carbon dioxide (CO_2)

Figure 10: Comparison of the correlation: range and median values for petrol cars.



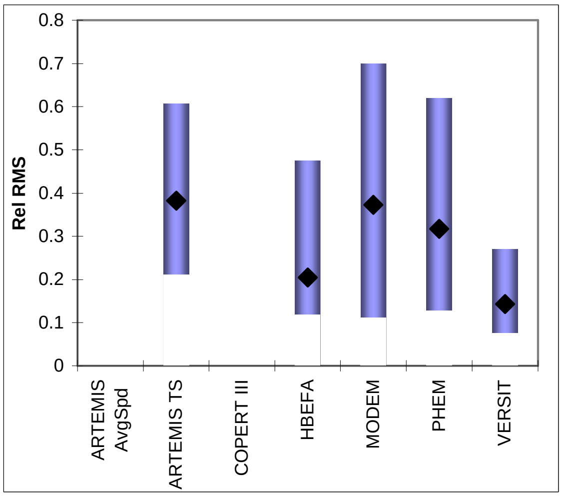
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



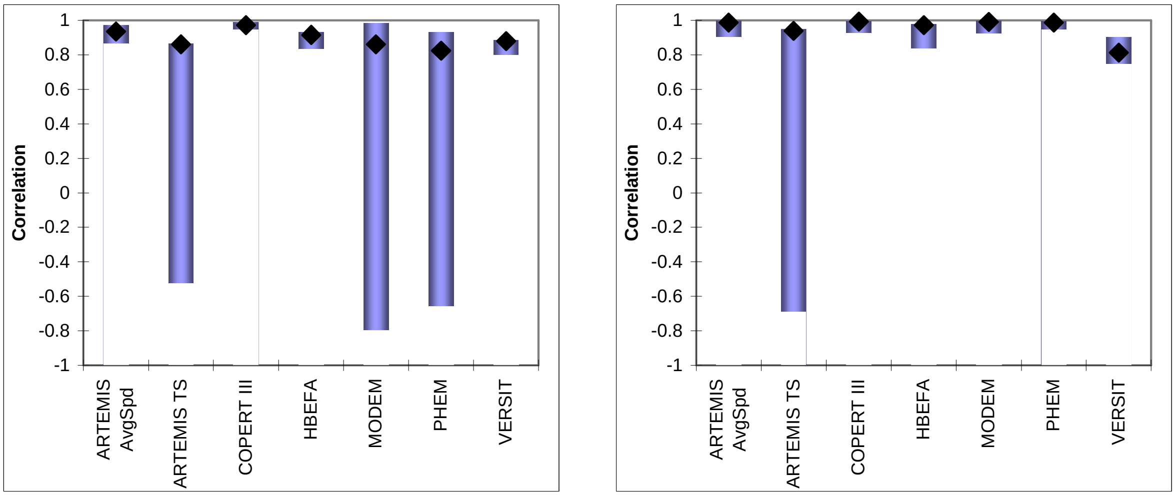
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



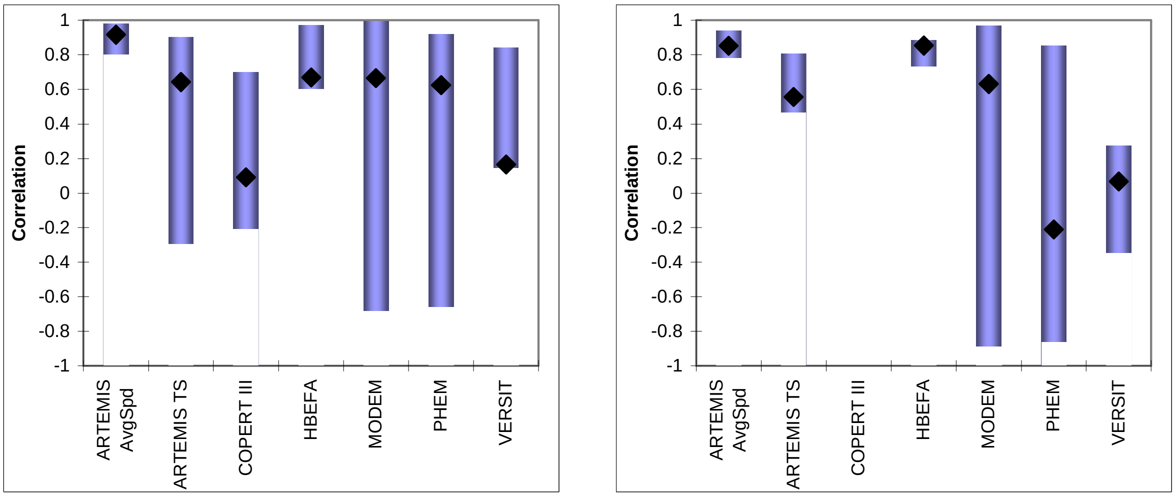
e. Carbon dioxide (CO_2)

Figure 11: Comparison of the relative RMS error: range and median values for petrol cars.



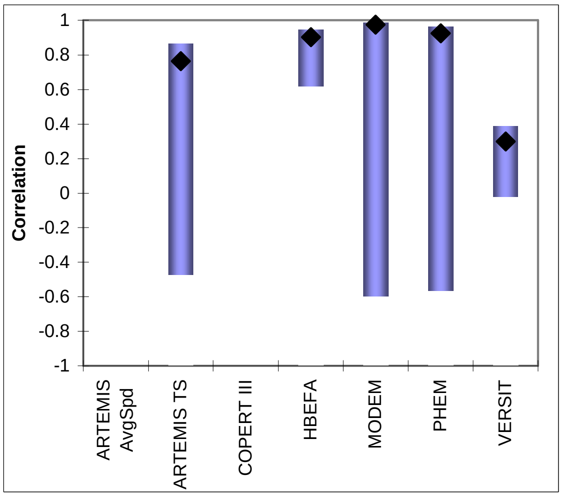
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



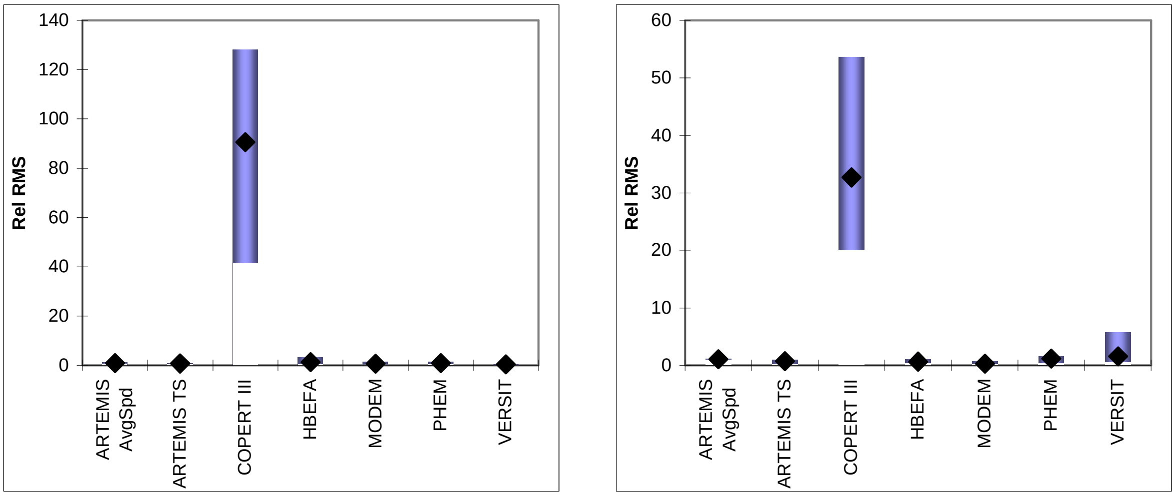
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



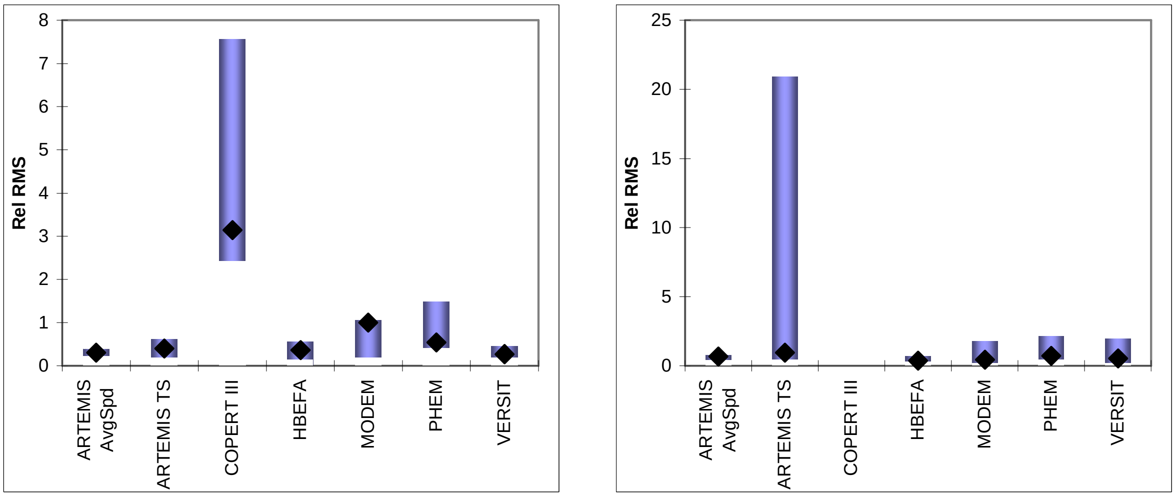
e. Carbon dioxide (CO_2)

Figure 12: Comparison of the correlation: range and median values for diesel cars.



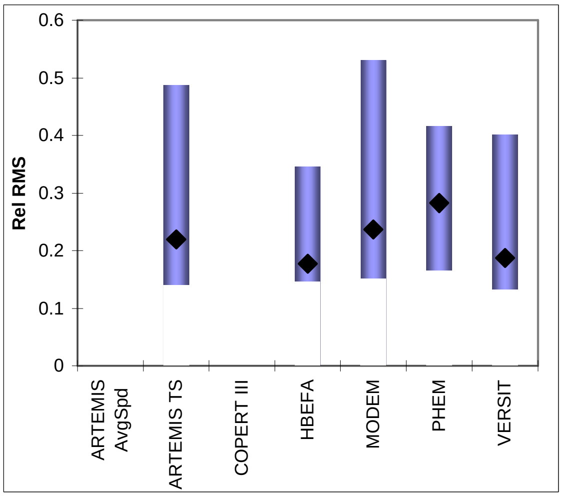
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



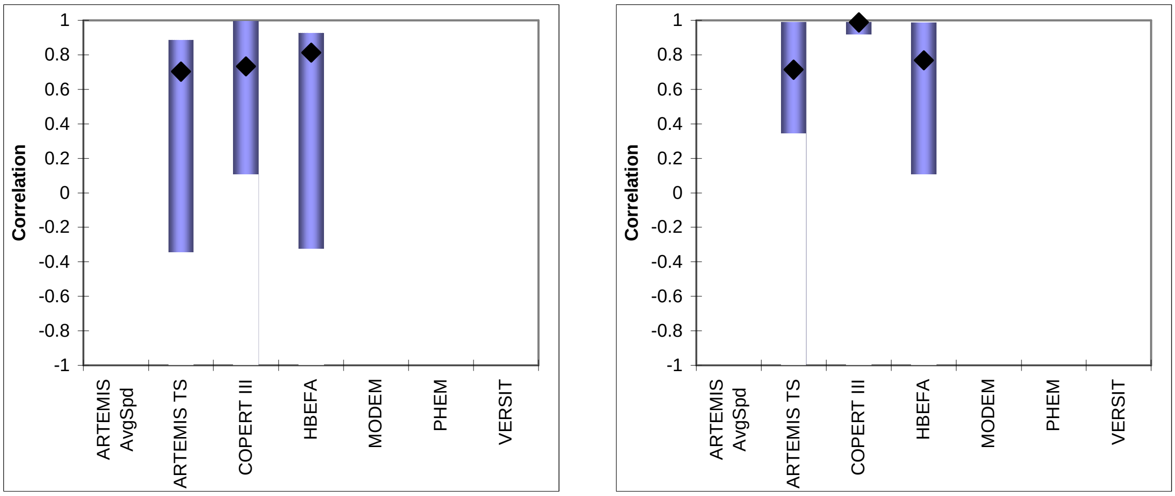
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



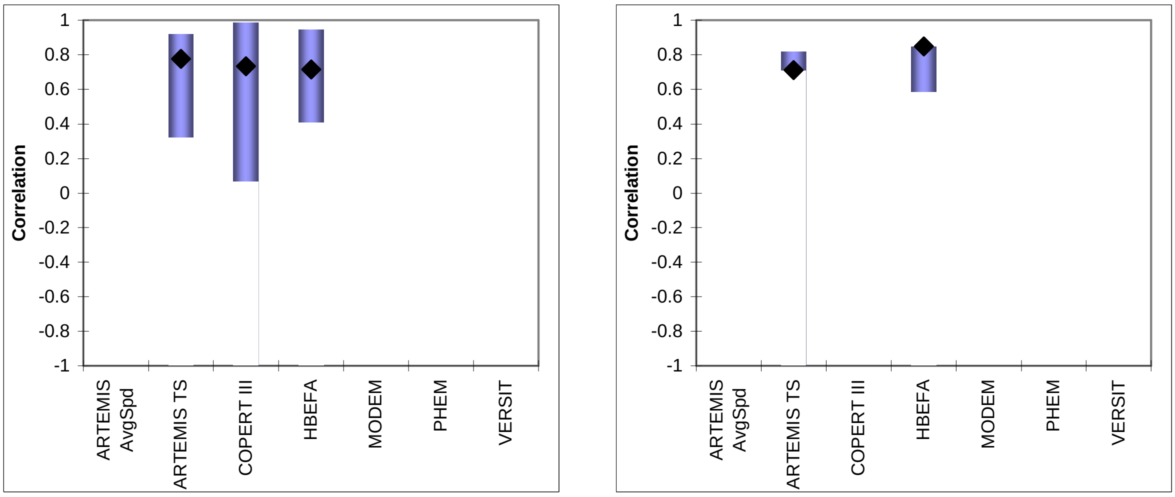
e. Carbon dioxide (CO_2)

Figure 13: Comparison of the relative RMS error: range and median values for diesel cars.



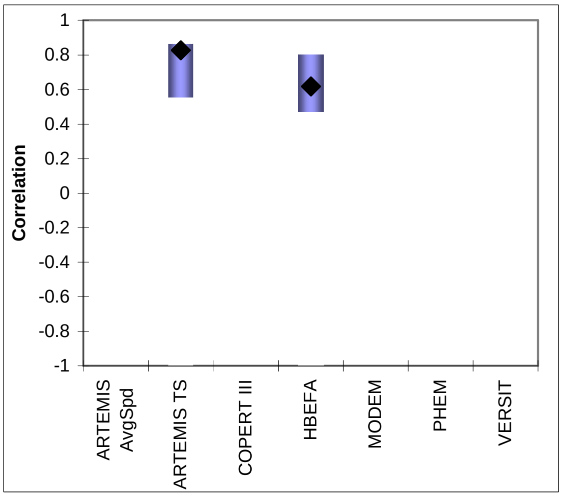
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



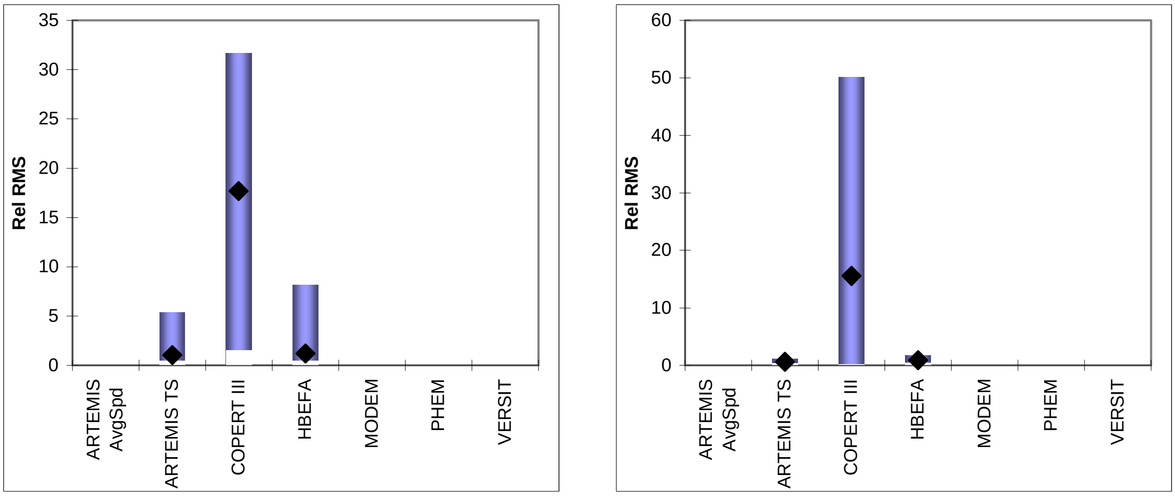
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



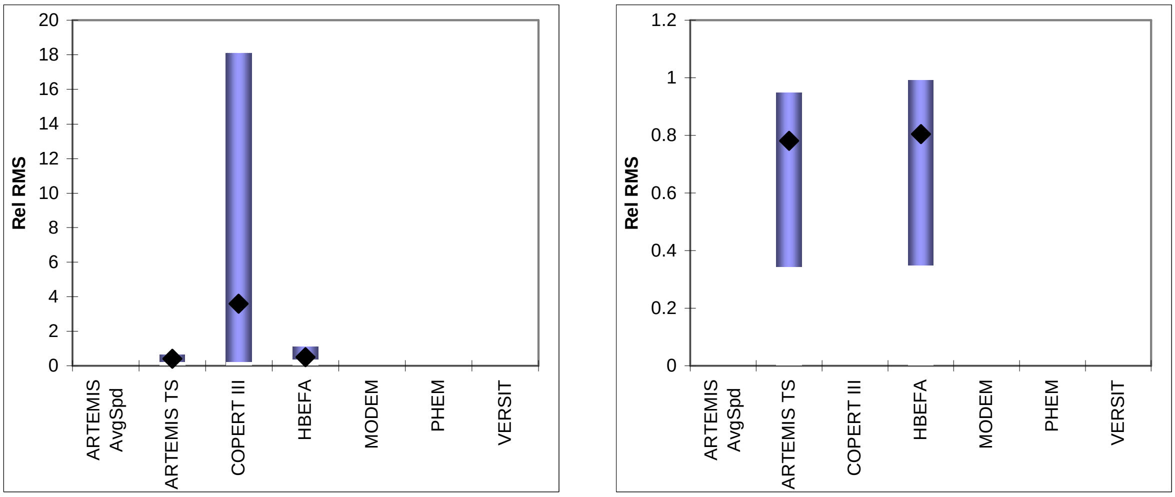
e. Carbon dioxide (CO_2)

Figure 14: Comparison of the correlation: range and median values for petrol and diesel LGVs.



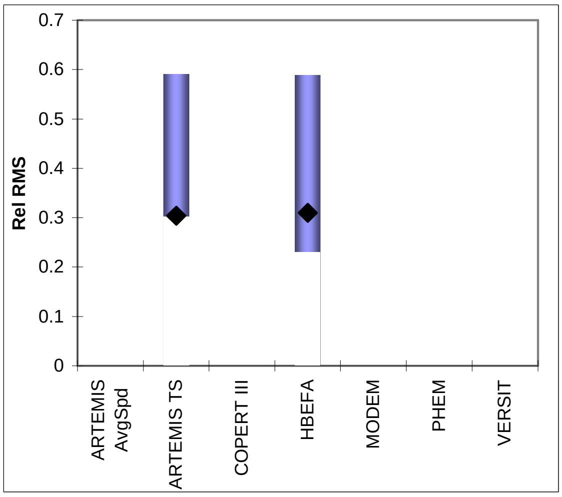
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



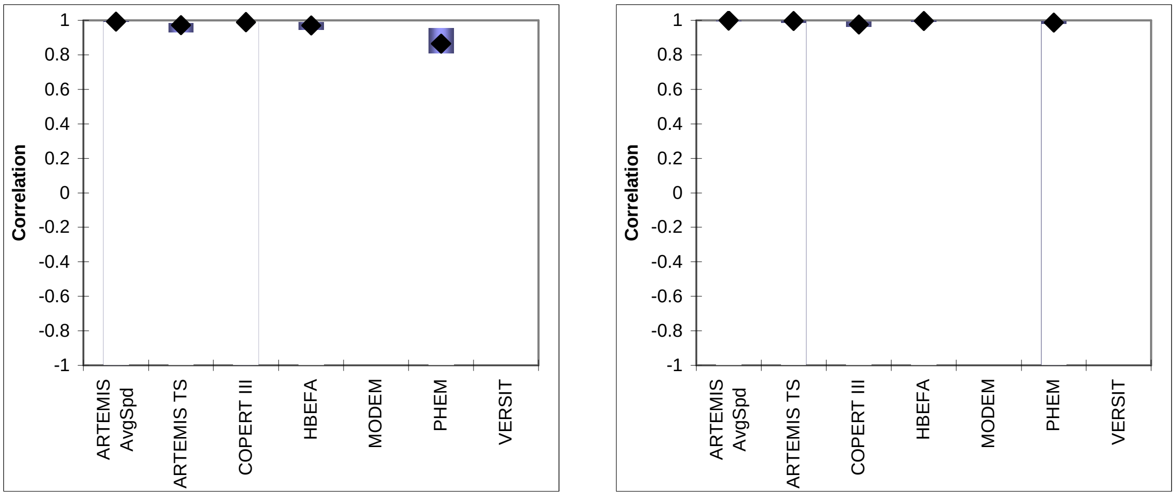
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



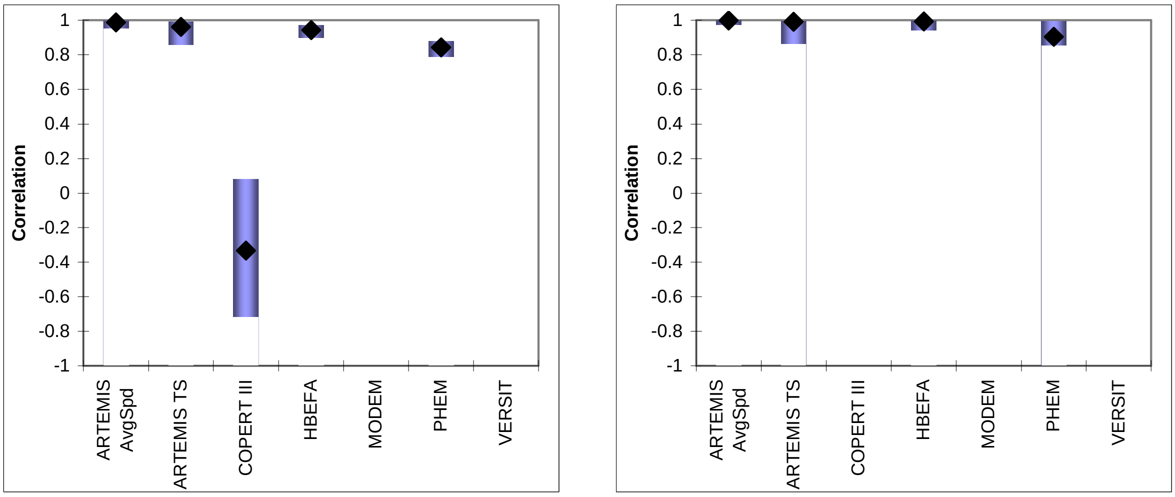
e. Carbon dioxide (CO_2)

Figure 15: Comparison of the relative RMS error: range and median values for petrol and diesel LGVs.



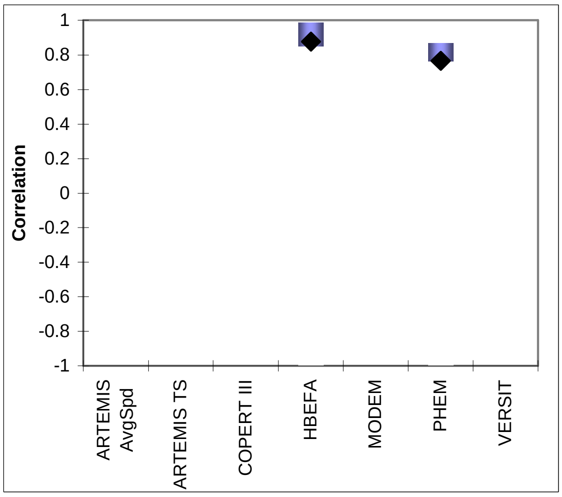
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



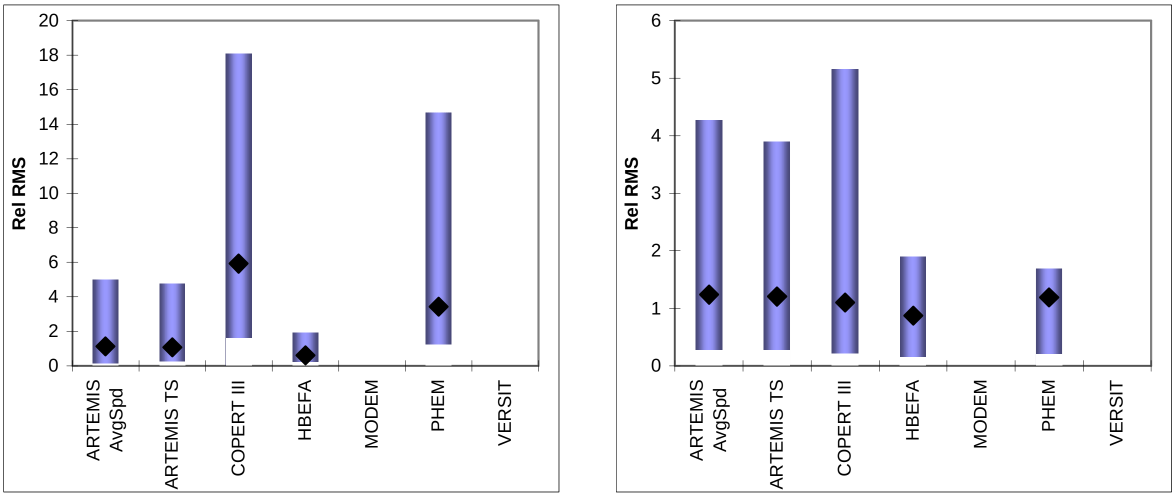
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)

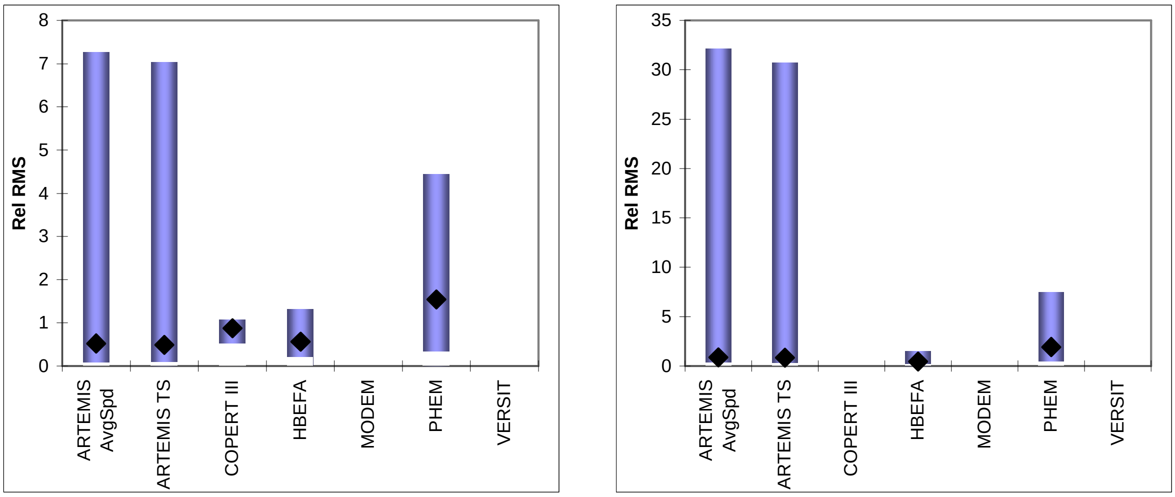


e. Carbon dioxide (CO_2)

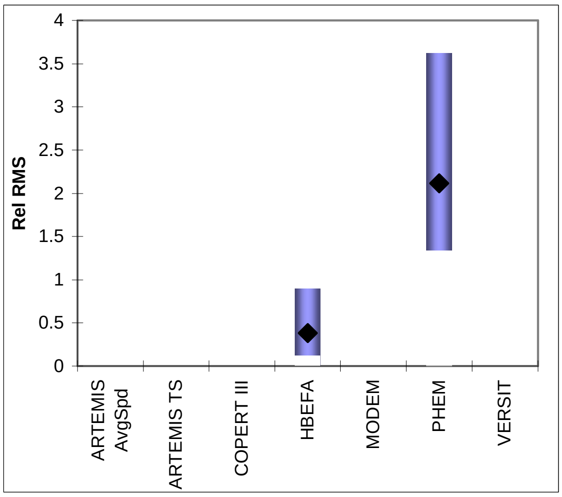
Figure 16: Comparison of the correlation: range and median values for HGVs.



a. Carbon monoxide (CO) *b. Hydrocarbons (HC)*

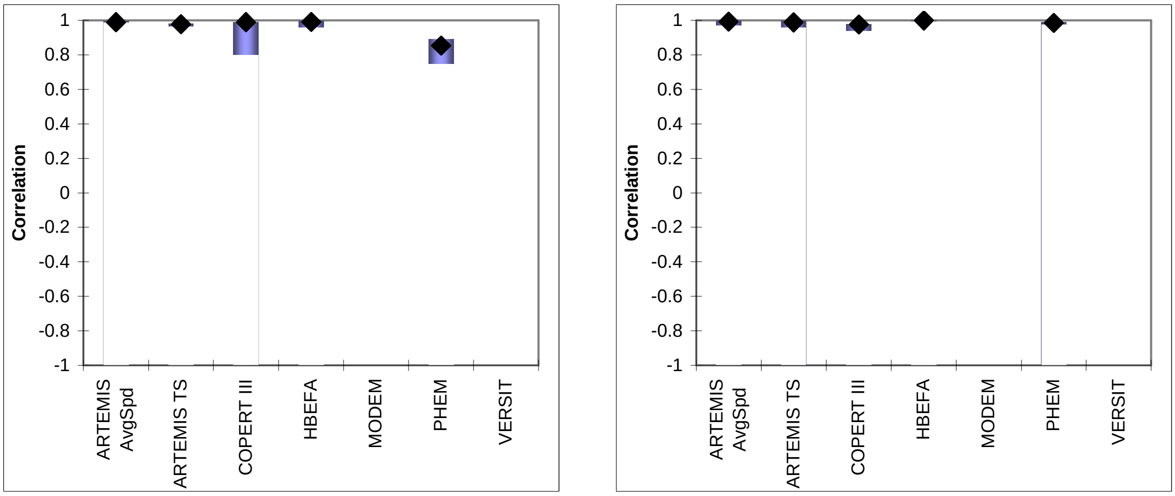


c. Oxides of nitrogen (NO_x) d. Particulate matter (PM)



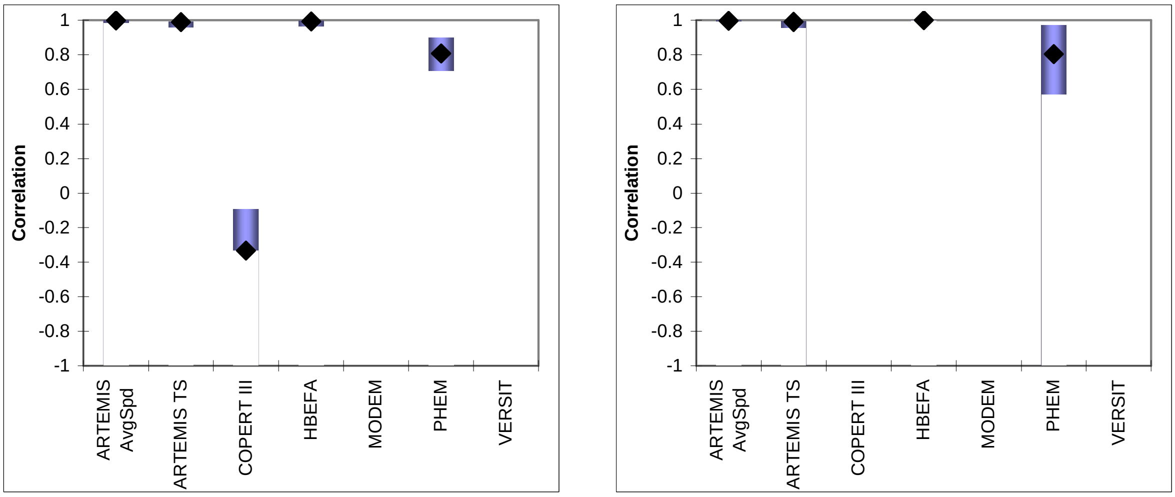
e. Carbon dioxide (CO_2)

Figure 17: Comparison of the relative RMS error: range and median values for HGVs.



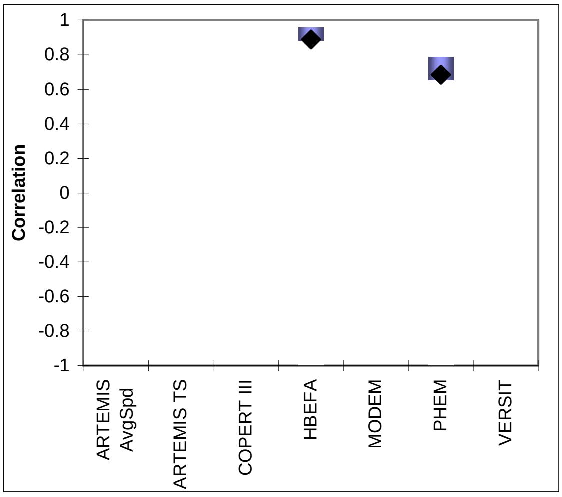
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



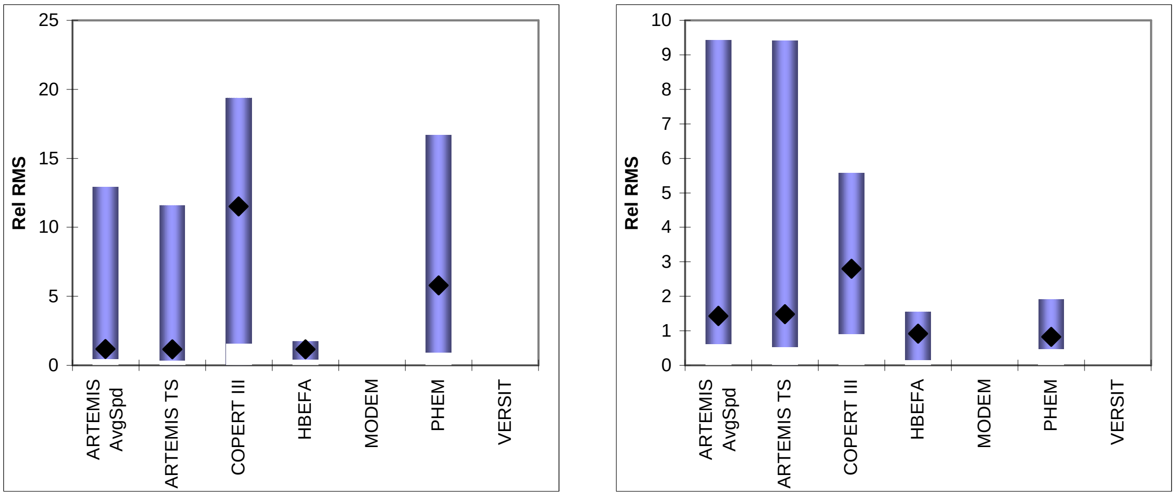
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



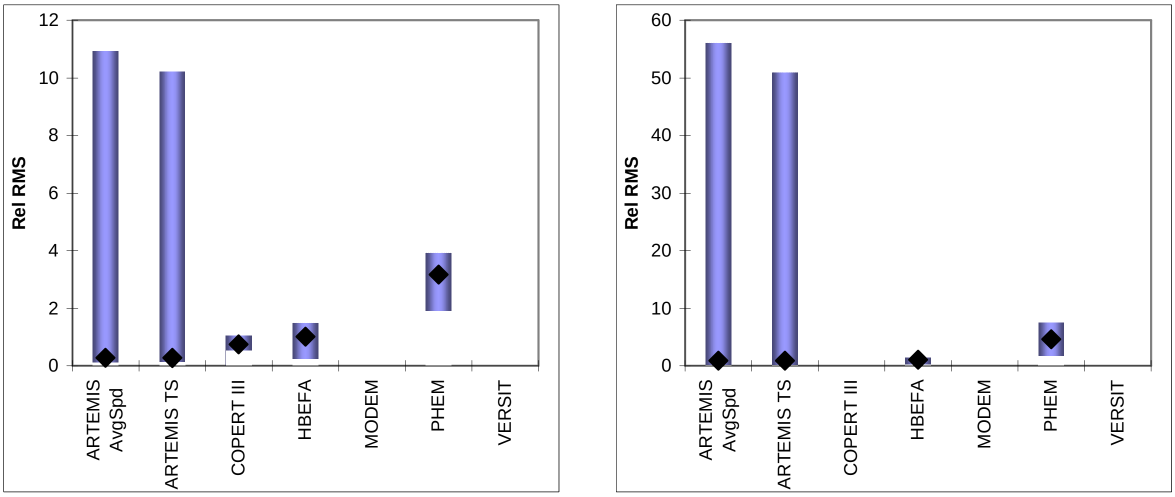
e. Carbon dioxide (CO_2)

Figure 18: Comparison of the correlation: range and median values for buses.



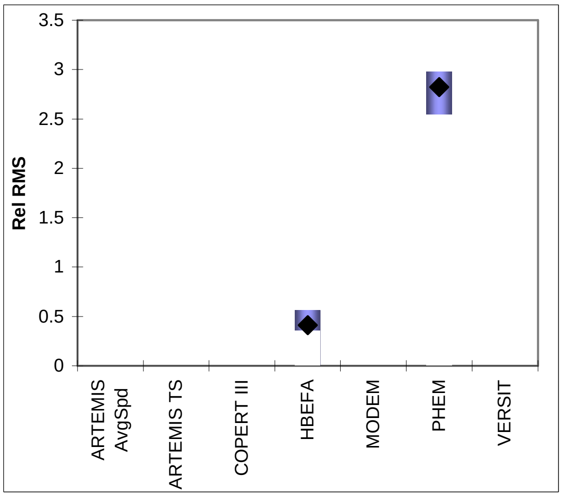
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



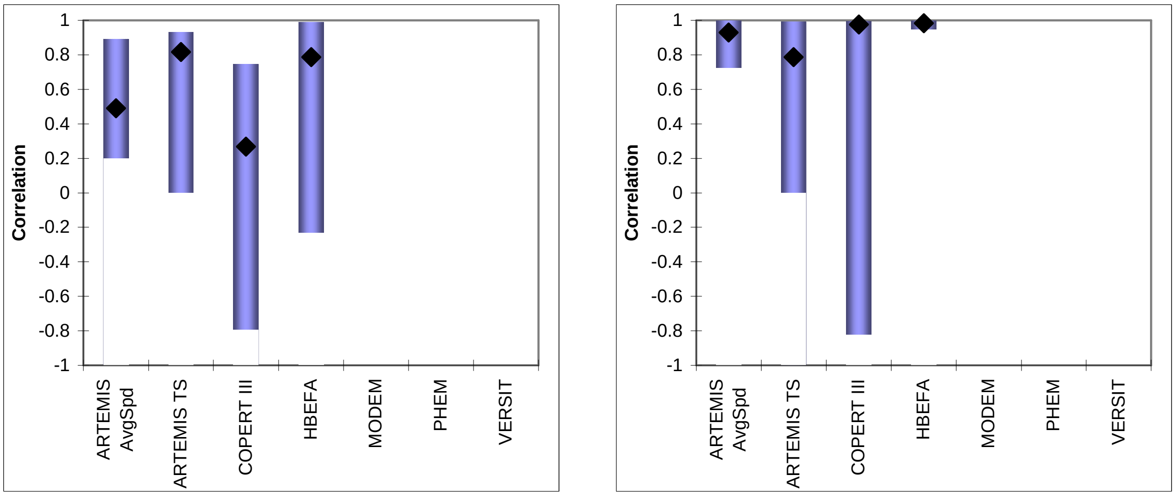
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



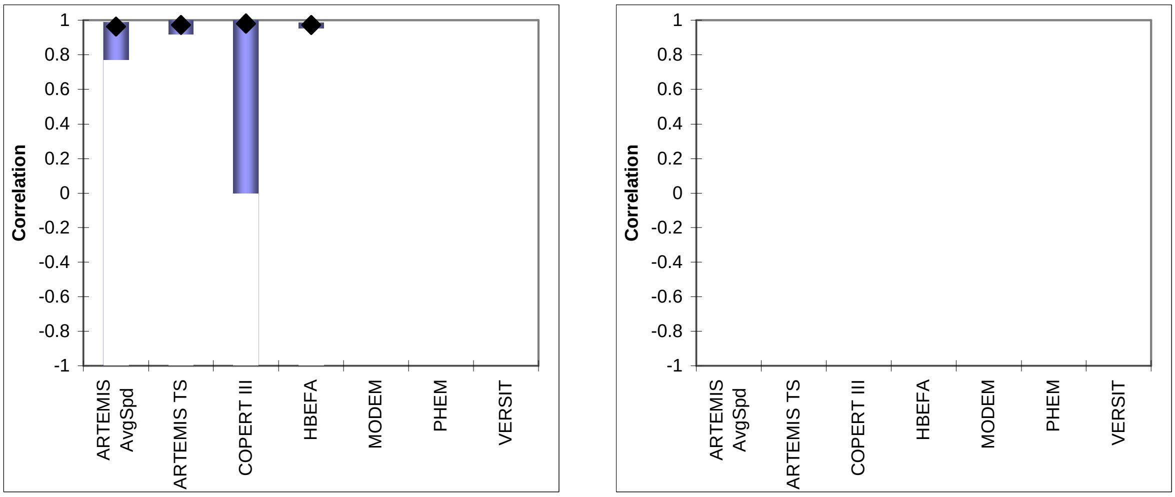
e. Carbon dioxide (CO_2)

Figure 19: Comparison of the relative RMS error: range and median values for buses.



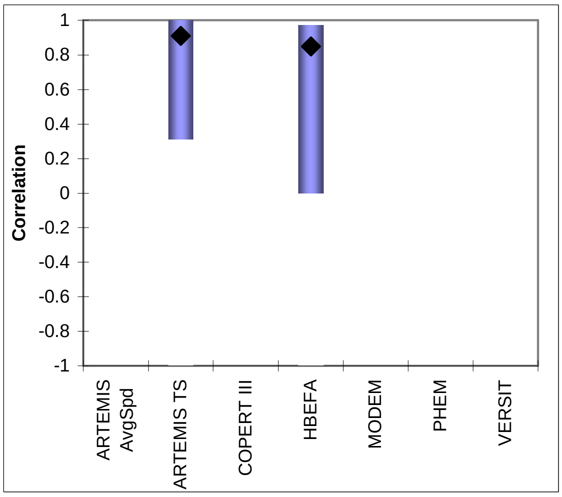
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



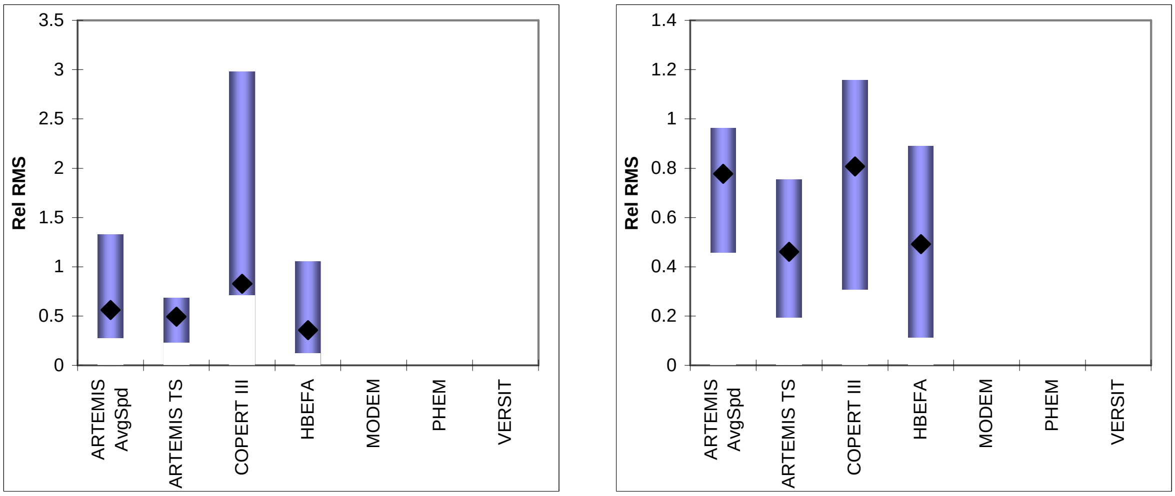
c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



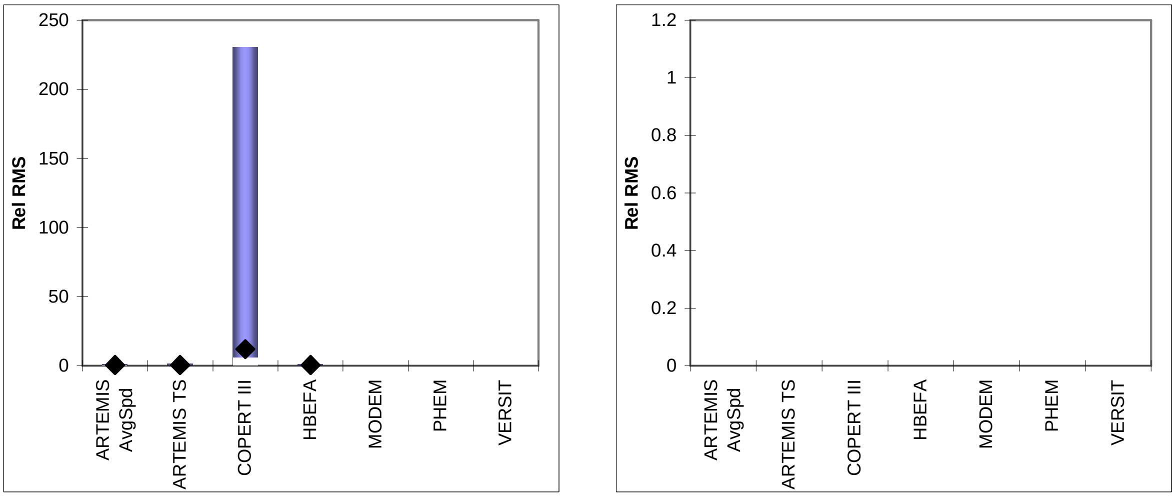
e. Carbon dioxide (CO_2)

Figure 20: Comparison of the correlation: range and median values for motorcycles.



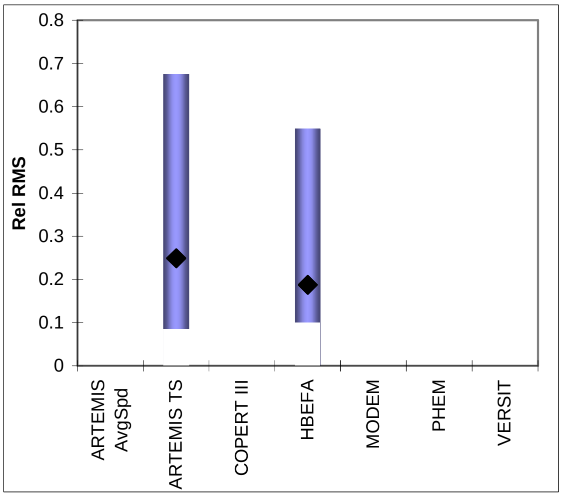
a. Carbon monoxide (CO)

b. Hydrocarbons (HC)



c. Oxides of nitrogen (NO_x)

d. Particulate matter (PM)



e. Carbon dioxide (CO_2)

Figure 21: Comparison of the relative RMS error: range and median values for motorcycles.

In order to further summarise the data and to allow the results to be more easily compared, the median correlations and relative RMS errors have been scored and colour coded according to schemes shown in Table 17. Here, green shading indicates a good agreement with the NAEI, orange shading indicates a moderate agreement, and red shading indicates a poor agreement. Within each colour band, asterisks or dashes are used to further refine the description of the agreement.

Table 17: Schemes used to score the correlations and the relative RMS error for the various models

Correlation coefficient	
0.8 to 1.0	*****
0.6 to 0.8	****
0.4 to 0.6	***
0.2 to 0.4	**
0.0 to 0.2	*
-0.2 to 0.0	-
-0.4 to -0.2	--
-0.6 to -0.4	---
-0.8 to -0.6	----
-1.0 to -0.8	-----

Relative RMS error	
0 to 0.25	*****
0.25 to 0.50	****
0.50 to 0.75	***
0.75 to 0.90	**
0.90 to 1.00	*
1.0 to 5	-
5 to 10	--
10 to 25	---
25 to 50	----
over 50	-----

The correlation coefficient (r) ranges from:

+1: indicating that the two emission curves (NAEI and the model being tested) are identical in shape.

to:

-1: indicating that the two emission curves have identical but opposite trends, *i.e.* a mirror image.

with

0: indicating that there is no relationship between the two emission curves

The relative RMS error ranges from zero (indicating the emission values are identical) to several hundred (indicating that there is a very large difference in the values).

The correlations are scored in Table 18. Generally, there was a very good agreement between the shapes of the emissions curves in the NAEI and those of the various models tested. The ARTEMIS (both traffic situation and average speed) and the PHEM emission factors have different shaped curves for CO and HC emissions from petrol cars, whilst the ARTEMIS traffic situation curves for NO_x also differ for petrol cars. COPERT produces different shaped curves for NO_x emissions from diesel cars, HGVs and buses. VERSIT+ has different trends for CO, HC and NO_x from petrol cars, NO_x and PM from diesel cars and CO_2 from both.

Table 19 lists the relative RMS error scores. This shows a variety of results ranging from very good comparisons to very poor ones. The best agreement between the models appears to be for NO_x and CO_2. For CO and HC, most of the comparisons appear to show poor agreement, whilst for PM there is almost an even split between good and poor agreements.

Blank spaces indicate that the model does not provide information for that particular vehicle/emission category.

Table 18: Summary comparison of the median correlations for the various models.

Pollutant	Vehicle group	Model						
		ARTEMIS AS	ARTEMIS TS	COPERT III	HBEFA	MODEM	PHEM	VERSIT+
CO	Petrol cars	--	--	*****	*****	****	--	-
	Diesel cars	*****	*****	*****	*****	*****	*****	*****
	Petrol and diesel LGVs		****	****	*****			
	HGVs	*****	*****	*****	*****		*****	
	Buses	*****	*****	*****	*****		*****	
	Motorcycles	***	*****	**	****			
HC	Petrol cars	**	**	*****	****	*****	-	-
	Diesel cars	*****	*****	*****	*****	*****	*****	*****
	Petrol and diesel LGVs		****	*****	****			
	HGVs	*****	*****	*****	*****		*****	
	Buses	*****	*****	*****	*****		*****	
	Motorcycles	*****	****	*****	*****			
NO_x	Petrol cars	***	*	*****	****	***	***	*
	Diesel cars	*****	****	*	****	****	****	*
	Petrol and diesel LGVs		****	****	****			
	HGVs	*****	*****	--	*****		*****	
	Buses	*****	*****	--	*****		*****	
	Motorcycles	*****	*****	*****	*****			
PM	Petrol cars							***
	Diesel cars	*****	***		*****	****	--	*
	Petrol and diesel LGVs		****		*****			
	HGVs	*****	*****		*****		*****	
	Buses	*****	*****		*****		*****	
	Motorcycles							
CO_2	Petrol cars		*****		*****	*****	*****	*
	Diesel cars		****		*****	*****	*****	**
	Petrol and diesel LGVs		*****		****			
	HGVs				*****		****	
	Buses				*****		****	
	Motorcycles		*****		*****			

Table 19: Summary comparison of the median relative RMS error for the various models.

Pollutant	Vehicle group	Model						
		ARTEMIS AS	ARTEMIS TS	COPERT III	HBEFA	MODEM	PHEM	VERSIT+
CO	Petrol cars	-	-	--	-	-	-	-
	Diesel cars	-	***	-----	-	***	*	****
	Petrol and diesel LGVs		-	---	-			
	HGVs	-	-	--	***		-	
	Buses	-	-	---	-		--	
	Motorcycles	***	****	**	****			
HC	Petrol cars	-	-	----	-	-	-	***
	Diesel cars	-	**	----	***	****	-	-
	Petrol and diesel LGVs		***	---	**			
	HGVs	-	-	-	**		-	
	Buses	-	-	-	*		**	
	Motorcycles	**	****	**	****			
NO_x	Petrol cars	*	***	--	***	***	*	**
	Diesel cars	****	****	-	****	-	***	****
	Petrol and diesel LGVs		****	-	***			
	HGVs	***	****	**	***		-	
	Buses	****	****	***	-		-	
	Motorcycles	***	***	---	***			
PM	Petrol cars							-
	Diesel cars	***	*		****	****	***	***
	Petrol and diesel LGVs		**		**			
	HGVs	**	**		****		-	
	Buses	**	*		-		-	
	Motorcycles							
CO_2	Petrol cars		****		*****	****	****	*****
	Diesel cars		*****		*****	*****	****	*****
	Petrol and diesel LGVs		****		****			
	HGVs				****		-	
	Buses				****		-	
	Motorcycles		*****		*****			

4 Evaluation of model and emission factor accuracy

4.1 Overview

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.

In this Chapter of the Report, a review is presented of emission factor validation exercises which relate to the models considered so far, and which have been based on real-world measurements. However, it should be noted that it is rather difficult to assess the absolute accuracy of different types of emission model in real-world situations, not least because there are substantial errors associated with the prediction of emissions. Examples of sources of error in emission modelling include the following:

Model selection: Not all models are suitable for all applications. For example, an average-speed model may not provide a useful simulation of emissions in a very specific situation, such as evaluating the effects of a traffic calming scheme.

Model data quality: If the measurements underpinning the model are flawed, then the output will be inaccurate.

Calculation method: Differences in model methodologies mean that the results may vary even if the same basic measurements are used.

Input data quality: If the quality of the input data is poor, the accuracy of the model prediction is likely to be low. This cannot be counteracted by the use of a more sophisticated model.

Representativeness: In order for a model to be representative the driving cycles and emissions data in the model need to be based upon real-world conditions. This is not always the case.

Vehicle performance: Measurements from a small sample of vehicles may be used to represent a fleet of millions. Two vehicles of the same type may perform differently under identical conditions, and so testing one vehicle may not produce results which are representative of the type as a whole. Therefore, emission factors need to be derived from tests based on a sufficient number of vehicles.

Vehicle classification: In Europe vehicles are classified in emission models by the emission legislation. The model user may also not have control over the proportions of each class of vehicle within the model. Some models use a ‘typical’ vehicle fleet composition, usually based on the annual total mileage nationally, which may not be typical of the local traffic situation.

Most emission models are based on the results of laboratory tests in which vehicles have been operated on a chassis dynamometer. The high cost of laboratory tests has meant that the models have tended to be based on small samples of vehicles. Few of these models have incorporated on-road emission data, and testing their accuracy and representativeness is problematic.

The review covers four main approaches to examining the accuracy of models and emission factors:

(i) *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.

(ii) *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.

(iii) *Inverse modelling*. 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.

(iv) *Measurements in 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.

4.2 Comparisons with on-board measurements

In December 2005 TRL fitted a car with a portable ‘garage-type’ exhaust emissions analyser and ran it along a section of the A1(M) motorway near Hatfield. The vehicle used was a medium sized Euro 3 petrol car. Concentrations of CO, HC, NO and CO_2 in the vehicle exhaust were measured. Additional instrumentation added to the car included a GPS receiver and a link to the vehicle’s OBD interface. Various parameters were logged via the OBD interface, including vehicle speed, engine speed and manifold air pressure. From the OBD information, the mass flow of the exhaust was estimated, and this was used with the measured concentrations to estimate the mass emissions.

Is should be noted that the measurements could only be viewed as indicative for a number of reasons, including the following:

- There were time delays in the response of the analyser, and some emission peaks may have been missed.
- During some types of operation the emissions may have been lower than the precision of the analyser.
- The exhaust mass flow was estimated based on information available from the OBD.
- The results from the system were not validated by comparison with a full emission test laboratory

In addition, although the analyser was calibrated by a NAMAS engineer prior to the test work, the engineer had no means of checking the calibration of the NO channel (as this is not checked for normal garage use).

The main aim of the work was to assess the usefulness of a simple, relatively inexpensive system for measuring emissions. Although there may be errors in the measured emissions, the analyser was able to identify where high emission episodes were occurring. These short-duration high-emission episodes accounted for a high proportion of the total emissions.

In this work, various emission models were also used to estimated the emissions over each trip, based on the actual logged driving pattern (*i.e.* the MODEM and PHEM models) or the average speed of the trip (*i.e.* the NAEI, COPERT III and ARTEMIS average-speed functions). Each trip was about 1.5 km long, and related to the same section of motorway (same direction), with the average speeds ranging from 75 to 113 km/h. The predicted emissions (in grammes per trip) are shown plotted against the measured values for the various pollutants in Figure 22.

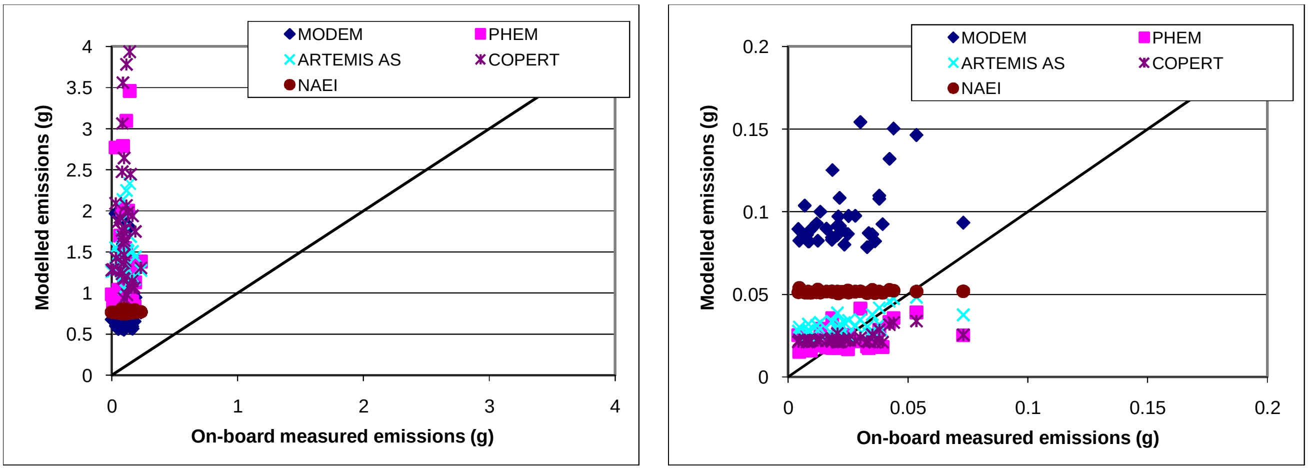
Each graph has equal ranges on both axes, and is marked with a diagonal line showing equality. Points plotted above this diagonal line indicate that the predicted emissions are higher than the measured values, and *vice versa*.

For CO and NO_x, the predicted emissions were much higher than the measured emissions – in fact very low values were actually measured.

For HC, all of the predicted emissions straddled the equality line, apart from the MODEM model which predicted higher values than were measured. The results for the average-speed functions generally produced a flat set of points on the graph. This was due to the measured speeds corresponding to the part of the HC emissions function where emissions vary only slightly with speed.

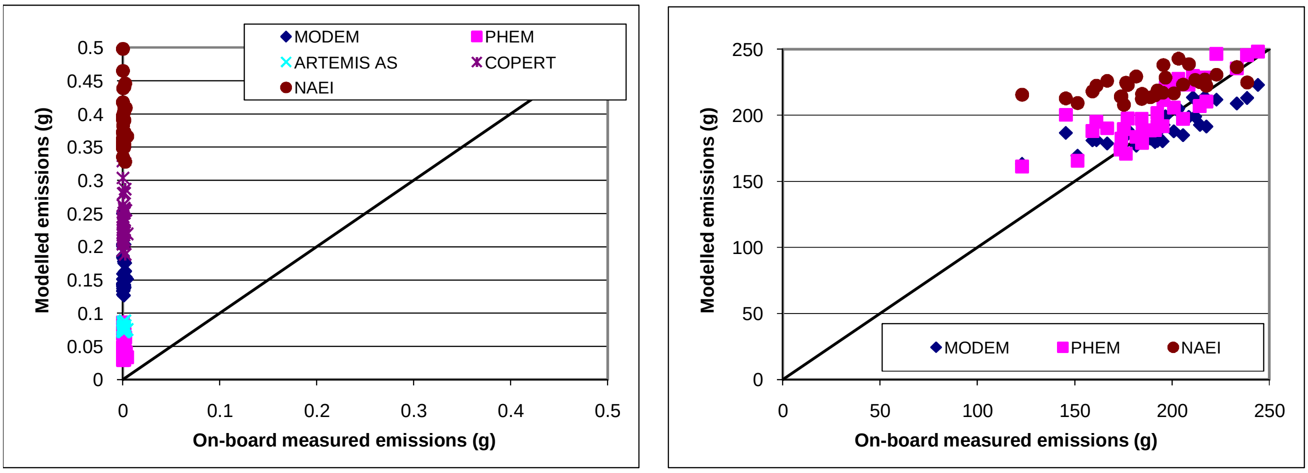
For CO_2 (only from MODEM, PHEM and NAEI), there was generally a good agreement between the predicted and measured values (the data points were either side of the equality line), although the NAEI tended to give slightly higher values than were measured. The agreement appears to be better for the higher emissions. For the lower emissions, the predicted emissions are higher than those measured.

Some of these differences in emissions may have been due to the inaccuracies in the measurement system. They may also have been a result of the (single) vehicle selected for the test work. For the average speed models the levels of accelerations actually encountered will affect the comparison (the average speed functions incorporate a set amount of acceleration, whereas the actual cycle driven can vary). For the instantaneous models the accelerations should be accounted for. However, the results do not show any obvious advantages of the instantaneous models over the average speed functions in predicting emissions.



a. CO emissions

b. HC emissions



c. NO/NO$_x$ emissions

d. CO$_2$ emissions

Figure 22: Comparison of modelled results with measured data

4.3 Comparisons with remote sensing measurements

The first successful devices for remotely sensing pollutant concentrations in vehicle exhaust plumes were introduced at the University of Denver in 1987 (Bishop *et al.*, 1989) and at the General Motors Research and Development Centre in 1988 (Stephens and Cadle, 1991). Although remote sensing was designed primarily for use as an inspection tool for road vehicles, it does have applications in other areas. Remote sensing devices can rapidly collect large quantities of emission data that naturally reflect the on-road vehicle fleet composition and include measurements on the newest vehicle technologies. This makes the use of remote sensing data in emission models and inventories, or for validating existing models, an attractive proposition. However, remote sensing only measures the percentage by volume of a given pollutant in vehicle exhaust plumes, and air quality impacts, whatever the context, are usually based on the mass of pollution released to the atmosphere. Therefore, for the potential of remote sensing to be fully realised in modelling applications there is a need to derive mass-based information (*i.e.* g km^{-1}) on pollutant emissions from the volumetric data. Such information is also desirable if remote sensing is to be used to test the validity of emission models.

A small number of studies have used remote sensing to either develop or test emission models, and these are summarised below. None of the examples relate directly to the UK emission factors.

Singer and Harley (1996) demonstrated how the emission factors measured by remote sensing could be combined with fuel sales data to calculate CO emission inventories at the regional level. In a fuel-based inventory emission factors (measured by remote sensing) are normalised to fuel consumption rather than distance travelled, and activity is measured as the amount of fuel consumed (based on tax revenues). However, the fuel-based inventory technique has not been widely applied to estimate HC emissions because of concerns that IR sensors underestimate total HC concentrations in vehicle exhaust.

Yu (1998) presented a vehicle emission model called ONROAD which incorporates the emission data collected at five highway locations in the Houston area using a remote sensing device. The model establishes relationships between on-road exhaust emission rates and a vehicle's instantaneous speed profile. Yu compared the results from ONROAD with those from the MOBILE and EMFAC models. In order to generate comparable emission factors ONROAD was used to calculate emissions over the FTP cycle. Generally, the ONROAD model resulted in the highest CO emission factors over the FTP cycle for the four vehicle categories studied (cars, vans, pick-up trucks and other trucks). Whilst MOBILE and EMFAC generated very similar CO emission curves, the emissions from ONROAD were higher at all but the lowest and highest speeds (8 km h^{-1} and 104 km h^{-1} respectively), for which EMFAC predicted higher emissions. Also, whereas emissions predicted by MOBILE and EMFAC exhibited a continual decrease between 8 and 88 km h^{-1}, ONROAD predicted a rapid decrease in emissions at speeds below 53 km h^{-1}, with a rather moderate increase thereafter.

More recently, Ekström *et al.* (2004) have evaluated the COPERT III model using a dataset from optical remote sensing emission measurements on a large number of vehicles at three different sites in Gothenburg, Sweden, in 2001 and 2002. The remote sensing dataset contained fuel-specific emissions (grammes of pollutant emitted per litre of fuel burnt) of CO, nitrogen oxide (NO) and HC, as well as speed and acceleration data for individual vehicles. For petrol cars, a total of approximately 20,000 records with valid CO and HC remote sensor readings, and 16,000 records with valid NO readings were available for the COPERT III evaluation. For diesel cars and heavy-duty vehicles the remote sensing dataset contained 1,100 and 650 records with valid NO readings, respectively. Average fuel-specific emission factors derived from the remote sensing measurements were compared with corresponding emission factors derived from COPERT III for urban, hot stabilised engine conditions and an average speed 45 km h^{-1}.

Figure 22 shows that there was a good agreement between the two methods for petrol car NO_x emissions for all COPERT III subsectors (*i.e.* cylinder volume classes) and technology classes (*e.g.* Euro 1, 2, 3). In the case of CO emissions, the agreement was poorer, with the model overpredicting emissions for all but one of the technology classes. For petrol car HC emissions the agreement was reasonably good, although there was a tendency for the model to overpredict emissions. There was also a relatively good agreement for NO_x emission factors for diesel cars (Figure 23). On the other hand, the 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.

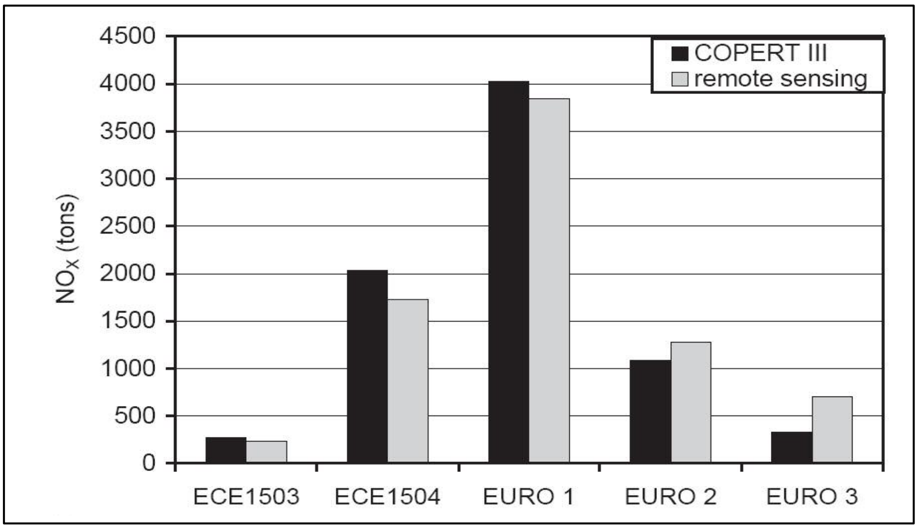


Figure 23: NO_x emission factors for petrol cars as calculated using COPERT III and measured with remote sensing (Ekström *et al.*, 2004)

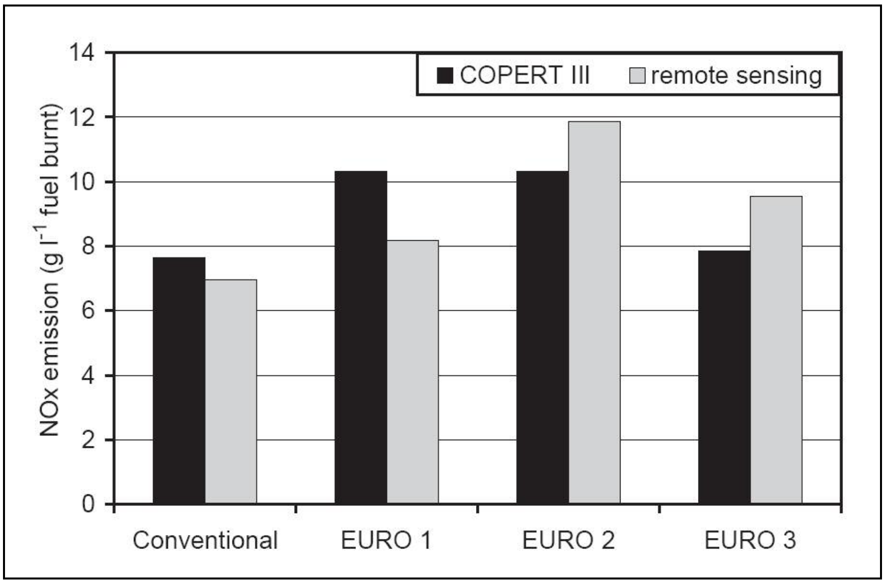


Figure 24: NO_x emission factors for diesel cars as calculated by COPERT III and measured with remote sensing (Ekström *et al.*, 2004).

Swedish national emissions of CO, NO_x and HC for petrol cars operating under hot stabilised conditions in urban traffic were estimated based on the emission factors derived in the study and available fuel consumption data. The resulting total CO emission using the COPERT III emission factors was 41% higher than when using the remote sensing emission factors. Similarly, for HC the COPERT III figure was 34% higher. For NO_x, however, the two methods resulted in almost exactly the same total emission. A comparison of NO_x emission factors for diesel cars demonstrated a reasonable agreement between COPERT III and the remote sensing data.

The study highlighted the potential and usefulness 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.

4.4 Inverse air pollution modelling

One approach for determining emission factors for road vehicles is to ‘invert’ an air pollution prediction model. The normal modelling approach involves the estimation of emissions from a stream of traffic, based on the combination of data relating to the flow, composition and speed of the traffic, and emission factors for specific vehicle categories. Algorithms are then used to determine the atmospheric concentrations of pollutants at specific locations (commonly known as ‘receptor points’), taking into account factors such as wind speed, wind direction, and chemical reactions in the atmosphere. However, if atmospheric pollutant concentrations are already known from measurements, and information on the traffic is available, then the vehicle emission factors can be estimated by model inversion, and this process has been tested here. It should be noted that this approach is relatively crude, and there are a number of potential sources of error. The following Sections describe the work undertaken by Barlow and Boulter (2007).

4.4.1 Method

Air pollution model inversion

The Design Manual for Roads and Bridges (DMRB) Screening Method was used for the calculations. In the DMRB, the emission of a given pollutant from the traffic per unit time and distance (g km^{-1} h^{-1}) can be calculated using simple information on traffic flow, composition and speed. In order to estimate the contribution of the traffic emissions to ambient roadside pollutant concentrations, pollutant dispersion is taken into account by converting the g km^{-1} h^{-1} emission values into ambient concentration values (µg m^{-3}) using a routine which applies to all pollutants. The contribution $\boldsymbol{c_{i,j}}$ (in µg m^{-3}) of the traffic on link $\boldsymbol{i}$ to concentrations of pollutant $\boldsymbol{j}$ at a distance $\boldsymbol{d_i}$ from the road centre is given by the following equations:

If 2m < d_i = 5m,

$$c_{i,j\,(\mathrm{road})} = \mathbf{0.063541} \quad \mu\mathrm{g\ m^{-3}\ g^{-1}\ km\ h} \qquad \text{(Equation 1)}$$

If 5m < d_i <= 168m,

$$c_{i,j\,(road)} = \frac{E_{i,j} \times \left[0.17887 + (0.00024\,d_i) - \left(\frac{0.295776}{d_i}\right) + \left(\frac{0.2596}{d_i^{\,2}}\right) - 0.0421\,\ln(d_i)\right]}{24} \quad \mu\mathrm{g\ m^{-3}}\ g^{-1}\ \mathrm{km\ h} \qquad \text{(Equation 2)}$$

If d_i > 168m,

$$c_{i,j(road)} = \frac{E_{i,j} \times [0.0017675 - (0.0000276173 \times (d_i - 168))]}{24} \quad \mu\mathrm{g\ m^{-3}\ g^{-1}\ km\ h} \qquad \text{(Equation 3)}$$

In order to determine the total pollutant concentration at the receptor point, the traffic-derived component must be added to the local background value:

$$C_{j\ total} = C_{j\ road} + C_{j\ background} \qquad \text{(Equation 4)}$$

Where:

$C_{j\ total}$ = total concentration of pollutant j at the receptor point
$C_{j\ road}$ = adjusted road traffic contribution to concentration of pollutant j at the receptor point
$C_{j\ background}$ = background concentration of pollutant j at the receptor point

In this work, the hourly mean values for $C_{j\ total}$ during 2004 were obtained from measurements at the AURN kerbside site at Marylebone Road, London. The pollutants included in the calculations were CO, NO_x and $PM_{2.5}$[17]. Hourly mean values for $C_{j\,background}$ were obtained from the AURN urban background site at Bloomsbury. For a given pollutant and each hourly period, the 'road traffic increment' concentration $C_{j\,road}$ (*i.e.* the pollution due to the local traffic) was calculated for Marylebone Road, by difference, using Equation 4. The air pollution monitoring site at Marylebone Road was estimated to be 12 m from the centre of the road. Consequently, Equation 2 was solved to give the traffic emission factor which corresponded to each hourly period. Based on the total traffic flow[18], an average vehicle emission factor was also calculated. Separate emission factors for LDVs and HDVs were then calculated using multiple regression analysis. The following regression model was applied to derive emission factors for CO, NO_x and $PM_{2.5}$:

$$E_{total} = (N_{LDV} \bullet E_{LDV}) + (N_{HDV} \bullet E_{HDV}) + c \qquad \text{(Equation 5)}$$

where:

E_{total} = the total hourly emissions from the traffic (the average emission factor per vehicle-km multiplied by the total number of vehicles).
N_{LDV} = the number of light-duty vehicles (all cars and LGVs) per hour
N_{HDV} = the number of heavy-duty vehicles (HGVs, buses and coaches) per hour
E_{LDV} = the emission factor for light-duty vehicles
E_{HDV} = the emission factor for heavy-duty vehicles
c = a constant

---

[17] Coarse particles ($PM_{2.5}$-PM_{10}) were excluded, as there are vehicle sources other than exhaust emissions (*e.g.* tyre wear, brake wear, resuspension).

[18] Motorcycles were excluded from this calculation, as they only form a small proportion of the traffic.

Emission modelling

Passenger car driving patterns were measured on Marylebone Road as part of the EU OSCAR Project. The measurements were conducted between 27 June and 2 July 2003 (Boulter *et al*., 2005). These driving patterns 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). A reference year of 2004 was used. The inverse model predictions gave results only for LDVs and HDVs. For LDVs account had to be taken of the emission factors for both cars and light goods vehicles (LGVs). Where models did not include specific emission factors for LGVs (ARTEMIS AS, PHEM, MODEM) the emission factors for large cars were used. It was assumed that LGVs formed 10% of the total LDV traffic. For each model, the distribution of Euro classes was taken from the NAEI (NETCEN fleet model), and the petrol/diesel splits for cars and LGVs were based upon the information in Web-TAG[19] Unit 3.5.6. As no driving patterns were available for HDVs, emissions from these vehicles were not modelled.

4.4.2 Results

Model inversion

The road traffic concentration increment was initially plotted as a function of time, and compared with the total traffic flow. It was clear that there were periods when the road traffic increment was closely related to the traffic flow (Figure 25, top graph). However, there were also periods when the road traffic increment bore little or no relation to the traffic flow (Figure 25, bottom graph).

It is also clear that the data from the bottom graph would not yield sensible emission factors from the traffic, and factors other than road traffic appear to have been affecting the measured concentrations. Consequently, the data for each pollutant were inspected visually, and periods when the relationship between the concentration increment and the traffic flow was poor were excluded from the analysis. The effects of this for NO_x can be seen in Figure 26, which shows the relationship between the NO_x road traffic emission factor and the traffic flow before and after the removal of 'incorrect' data, as described above. The results of the multiple regression analysis, based on the 'corrected' data, are given in Appendix B. The resulting emission factors are summarised in Table 20.

Emission model predictions

The comparisons between the results of the inverse modelling and the predictions of the different models are shown for LDVs in Figures 26-28. It can be seen that the CO and NO_x emission factors obtained by inverse modelling 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 (UKEFD) method.

There was found to be a discrepancy between the average speed on Marylebone Road which was derived from the traffic count site (40.2 km h^{-1}) and the average speed of all the OSCAR driving patterns (20.4 km h^{-1}). Figure 30 shows the OSCAR driving patterns on Marylebone approximate location of the traffic counting site near to the middle of the link. It is therefore possible that the OSCAR driving patterns are biased towards low speeds. Consequently, the trips which had an average speed near the monitoring site of between 30 and 50 km h^{-1} were treated as a separate sub-sample. However, the effect of using this sub-sample with higher speeds was generally to decrease the emission factors produced by the models, and so the difference in speed is probably not the main reason for the discrepancy between the inverse model and emission model predictions.

It is unlikely (though possible) that the predictions of the different emission models are systematically wrong. There are also a number of errors associated with the inverse modelling approach (see also the poor model fits in Appendix B), and further testing and refinement is required before this can be viewed as a reliable means of testing the accuracy of emission models.

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[19] http://www.webtag.org.uk/. The web-TAG site provides detailed guidance on the appraisal of transport projects, and wider advice on scoping and carrying out transport studies.

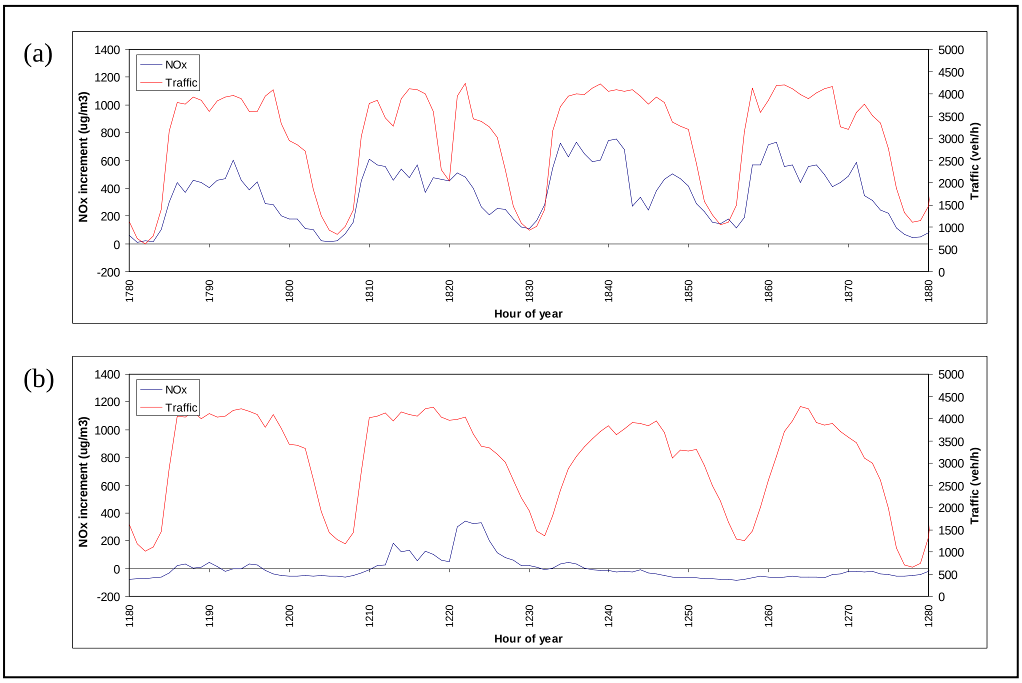
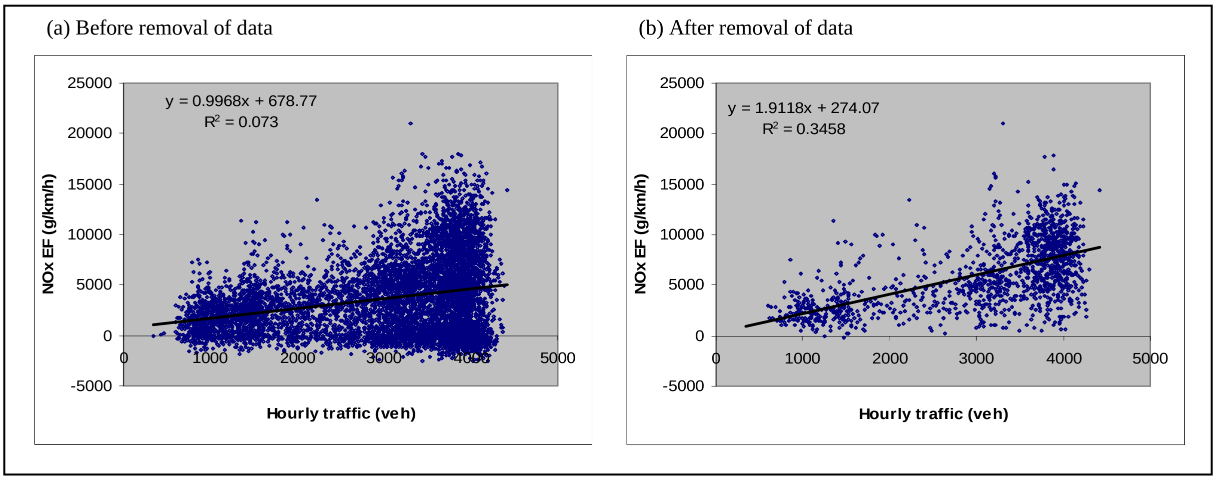


Figure 25: Road traffic increment for NO_x and total traffic flow on Marylebone Road for two different periods of 2004: (a) ‘good’ relationship between traffic flow and NO_x increment and (b) ‘poor’ relationship between traffic flow and NO_x increment.


(a) Before removal of data

(b) After removal of data

Figure 26: Relationship between total traffic flow and NO_x emission factor before and after the removal of ‘incorrect’ data.

Table 20: Emission factors on Marylebone Road for LDVs and HDVs in 2004, based on multiple regression analysis.

Pollutant	Vehicle category	Emission factor (g vehicle^{-1} km^{-1})	95% confidence intervals (g vehicle^{-1} km^{-1})	
			Lower limit	Upper limit
CO	LDV	7.04	6.54	7.53
	HDV	1.78	-0.20	3.76
NO_x	LDV	0.996	0.82	1.17
	HDV	6.99	6.31	7.67
$PM_{2.5}$	LDV	0.035	0.030	0.040
	HDV	0.25	0.23	0.27

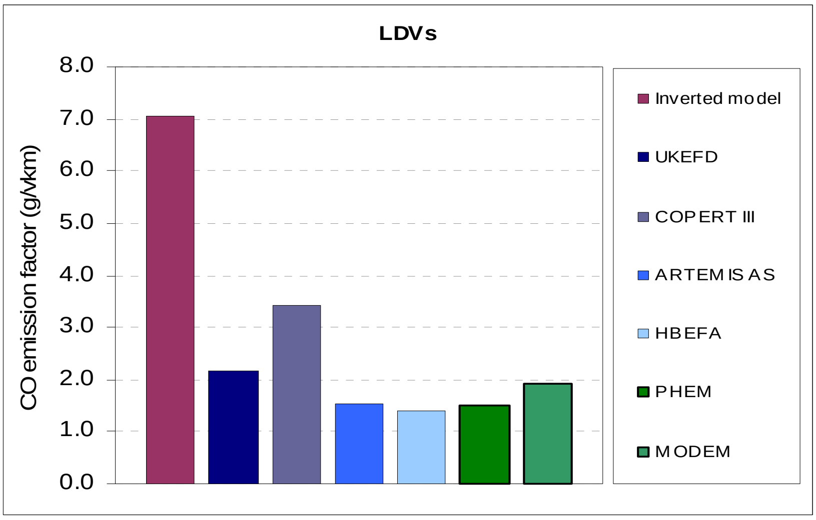


Figure 27: CO emission factors for LDVs.

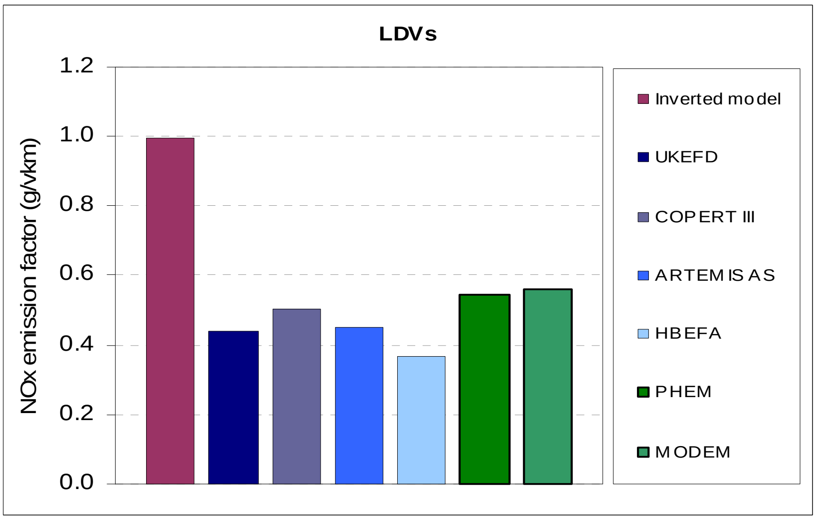


Figure 28: NO_x emission factors for LDVs.

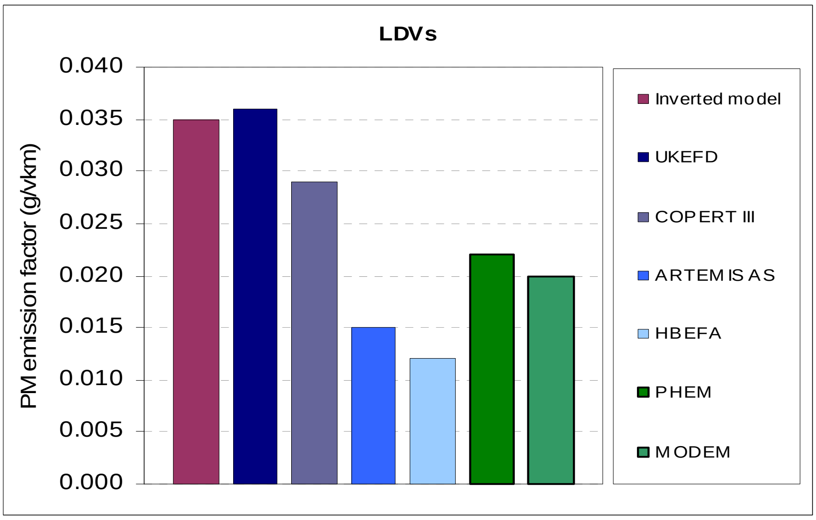


Figure 29: PM emission factors for LDVs.

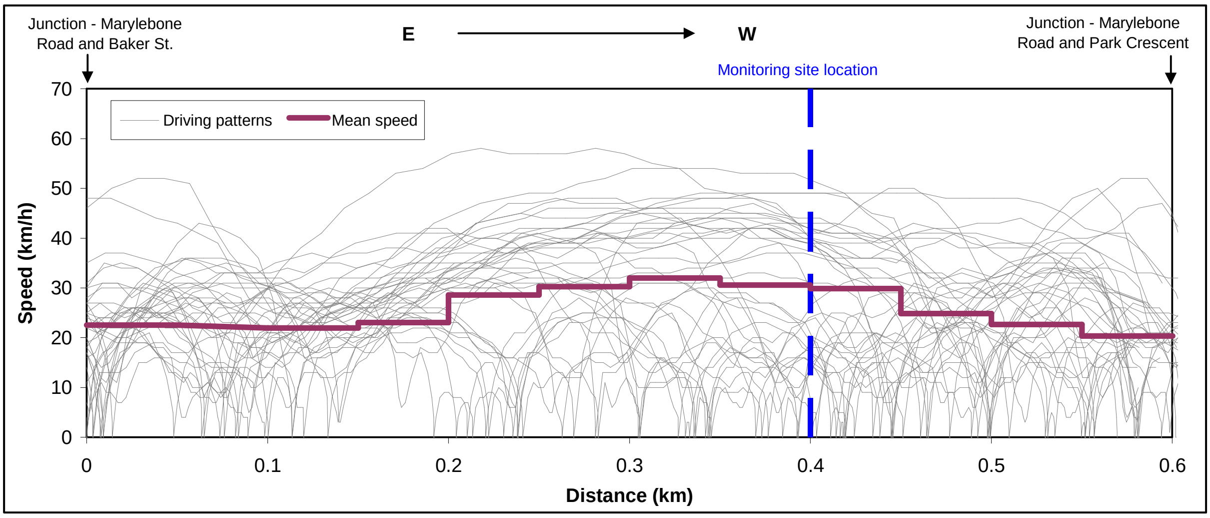


Figure 30: Driving patterns on Marylebone Road, and approximate location of traffic counting site.

4.5 Comparisons with measurements in tunnels

4.5.1 ARTEMIS

In ARTEMIS, measurements were conducted in three different road tunnels:

(i)	The Lundby tunnel	(Gothenburg, Sweden)
(ii)	The Plabutsch tunnel	(Graz, Austria)
(iii)	The Kingsway tunnel	(Liverpool, United Kingdom)

The main objective of this part of the ARTEMIS work was to derive new real-world emission factors in order to improve the accuracy of existing emission models. A statistical analysis was undertaken for each tunnel in order to determine emission factors for different vehicle categories. For each of the three tunnels, the average emission factors for LDVs and HDVs derived from the tunnel study were compared with those from the ARTEMIS model and national models. The results for the Kingsway tunnel are of most interest here.

Emissions in the Kingsway tunnel were calculated using the DMRB (Version 1.02g, with the 2002 UKEFD) for each hour of the Kingsway Tunnel experiment. The total numbers of vehicles in each category (car, LGV, Bus, Rigid HDV and Articulated HDV) were based upon toll information. In order to disaggregate the toll information, average ratios were used (*e.g.* the car proportion of LDVs) for each hour based on video survey information. The within-category distributions of Euro class and engine size were also based on the video surveys. The same average fleet profile was used for all time periods. Motorcycles were excluded from the calculation.

The results for the Kingsway tunnel are shown in Figures 30 to 35. The CO emission factor for LDVs from the ARTEMIS model was much higher than that from the tunnel measurements (‘Kingsway EF’) and the DMRB. For HDVs the DMRB prediction showed a good level of agreement with the tunnel measurements, but the ARTEMIS emission factor was lower. The LDV emission factor for NO_x derived using the DMRB also showed a good agreement with the tunnel measurements, whereas the ARTEMIS emission factor was again somewhat higher. In the case of HDVs, both the DMRB and ARTEMIS emission factors were lower that the emission factor derived from the tunnel measurements. This was similar to the result for NO_x, and Rodler *et al*. (2005) suggested that the reason for the underestimation of NO_x and CO_2 from HDVs could be related to vehicle load, which was not well known and which has large influence on CO_2 emissions. Furthermore, the road gradient in the Kingsway tunnel (-4%/+4%) could not be fully taken into account.

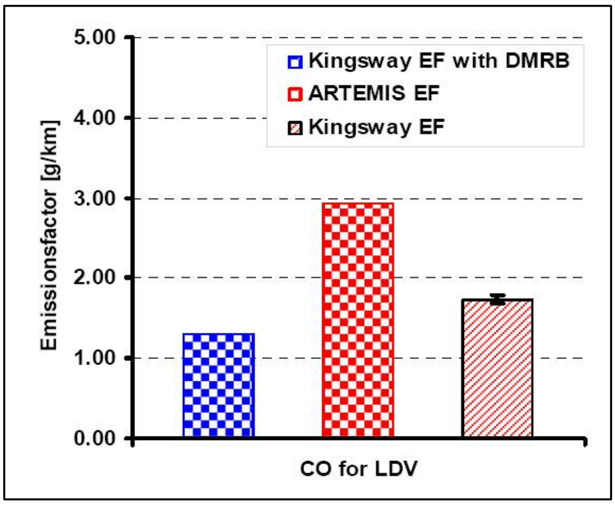


Figure 31: CO emission factors in Kingsway tunnel for LDVs (Rodler *et al.*, 2005).

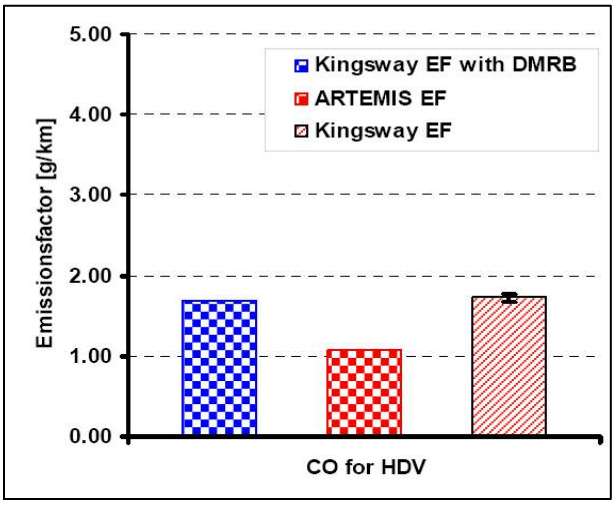


Figure 32: CO emission factors in Kingsway tunnel for HDVs (Rodler *et al.*, 2005).

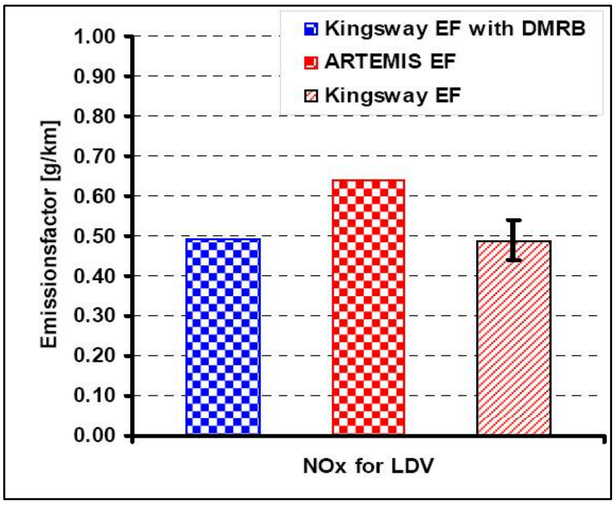


Figure 33: NO_x emission factors in Kingsway tunnel for LDVs (Rodler *et al.*, 2005).

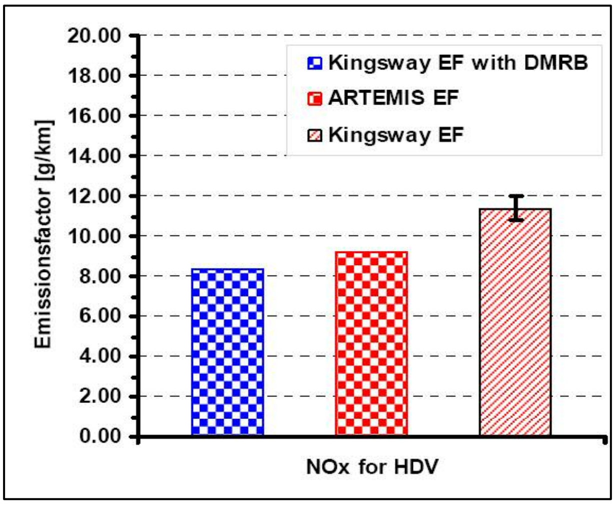


Figure 34: NO_x emission factors in Kingsway tunnel for HDVs (Rodler *et al.*, 2005).

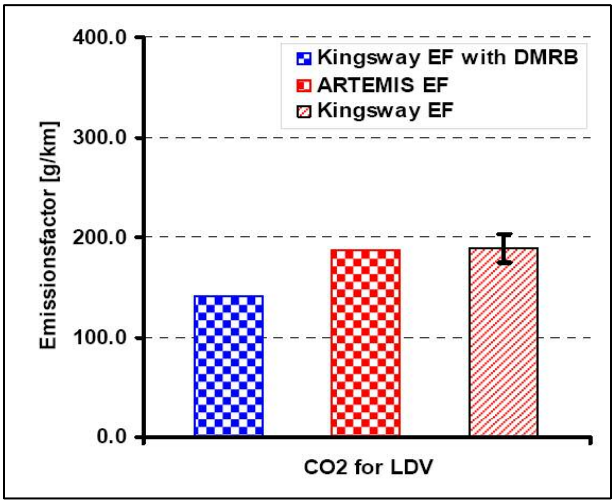


Figure 35: CO_2 emission factors in Kingsway tunnel for LDVs (Rodler *et al.*, 2005).

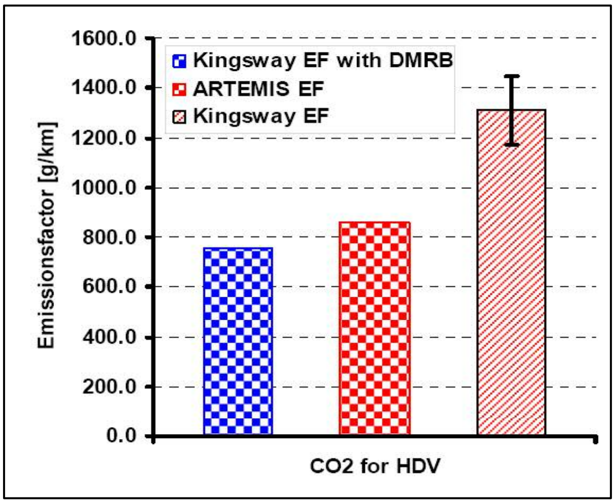


Figure 36: CO_2 emission factors in Kingsway tunnel for HDVs (Rodler *et al.*, 2005).

4.5.2 TRL measurements in Hatfield and Bell Common tunnels

Study method and results

Air pollution measurement campaigns were conducted by TRL in the Hatfield tunnel on the A1(M) between November 2005 and February 2006, and in the Bell Common tunnel on the M25 between May 2006 and January 2007 (Boulter *et al.*, 2007). In each tunnel continuous measurements were made of NO, NO_2 and O_3 at three locations: (i) close to the tunnel entrance, (ii) close to the tunnel mid-point and (iii) close to the tunnel exit. NO and NO_2 were measured using chemiluminescence analysers, and ozone was measured using UV absorption analysers. The analysers were positioned on the near-side walkway, and were separated from the traffic by the hard shoulder. The air pollution measurements were supplemented by the measurement of meteorological conditions. Induction loops permanently installed in the road surface were used to characterise the traffic. The differences between the hourly mean NO_x concentrations at the tunnel exit and tunnel entrance were used to determine average fleet-weighted NO_x emission factors, and NO_x emission factors for different vehicle categories were estimated using multiple regression analysis.

In addition, in the Hatfield tunnel a single car (petrol, Euro 3) was equipped for the measurement of driving patterns according to the input data requirements of the instantaneous models MODEM and PHEM. This vehicle was driven repeatedly through the tunnel at different times of day, with a total of 36 driving patterns being recorded. As in the inverse modelling exercise the average speeds of the driving patterns were used in the other models (apart from HBEFA, for which a traffic situation description was used).

The NO_x and NO_2 emission factors from the two tunnels are summarised in Table 21. The values are rounded to two decimal places and are shown with 95% confidence intervals. The emission factor values for NO_x and NO_2 were then used to calculate the NO_2/NO_x proportions, expressed as percentages, and these results are also given in Table 21. As the NO_x emission factors are calculated as NO_2 equivalents, the NO_2/NO_x proportions would be the same if converted to volumetric units.

Table 21: Summary of NO_x and NO_2 emission factors and NO_2/NO_x proportions. The numbers in brackets are the 95% confidence intervals (Boulter *et al.*, 2007).

Tunnel	Vehicle type	Emission factor (g vehicle^{-1} km^{-1})		NO_2/NO_x (%)
		NO_x	NO_2	
Hatfield	Cars and small LGVs	0.27 (± 0.05)	0.04 (± 0.01)	16
	Large LGVs	1.17 (± 1.19)	0.29 (± 0.14)	25
	Rigid HGVs	5.37 (± 2.22)	0.59 (± 0.27)	11
	Articulated HGVs	3.78 (± 2.22)	0.33 (± 0.27)	9
Bell Common	All LDVs	-0.32 (± 0.08)	0.04 (± 0.01)	N/A
	All HDVs	17.12 (± 0.46)	0.98 (± 0.05)	6

These final results show rather different situations in the two tunnels, with emissions in the Bell Common tunnel being dominated by heavy-duty vehicles. On the other hand, the largest NO_2/NO_x proportions were obtained for light-duty vehicles in the Hatfield tunnel, which is a rather surprising result given that a substantial proportion of the light-duty vehicle fleet is composed of vehicles with petrol engines, which have previously been found to have a relatively low NO_2/NO_x proportion.

Comparisons with model predictions

The comparisons between the NO_x emission factors derived from the tunnel measurements and the emission factors for the corresponding conditions and periods derived using the UK emission factors are shown in Figures 36, 37 and 38.

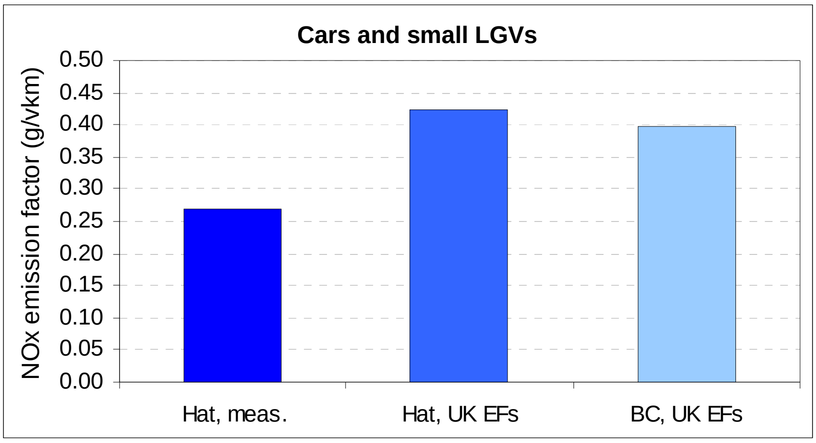


Figure 37: NO_x emission factors for cars and small LGVs based on the measurements in the Hatfield tunnel ('Hat, meas.') and derived using the UK emission factors for the Hatfield ('Hat, UK EFs') and Bell Common ('BC, UK EFs') tunnels.

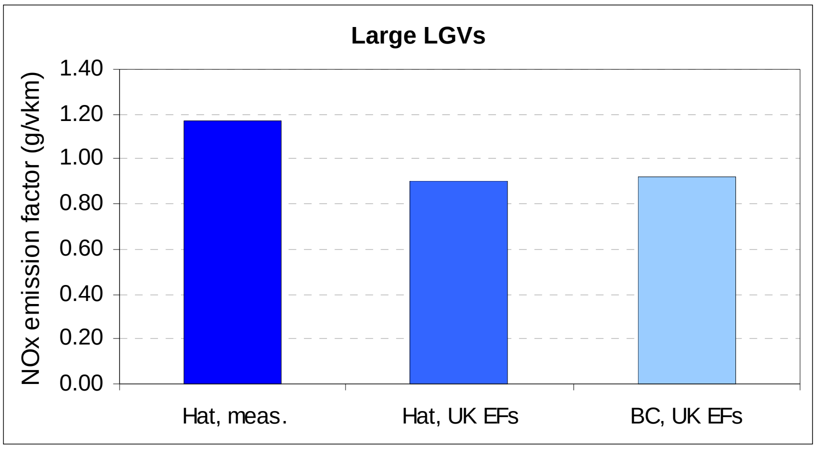


Figure 38: NO_x emission factors for large LGVs based on the measurements in the Hatfield tunnel ('Hat, meas') and derived using the UK emission factors for the Hatfield ('Hat, UK EFs') and Bell Common ('BC, UK EFs') tunnels.

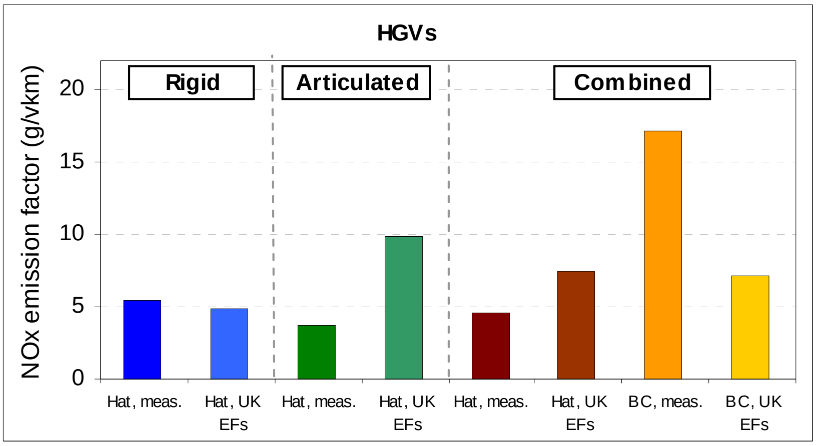


Figure 39: NO_x emission factors for HGVs based on the measurements in the Hatfield and Bell Common tunnels. The values derived using the UK emission factors are also shown.

It can be seen from Figure 37 that the emission factor for cars and small LGVs derived from the Hatfield tunnel measurements was slightly lower than the UK emission factor. The relative proportions of petrol and diesel cars in the fleet may have been important in this respect. For the calculation of the UK emission factor it was assumed that 25% of all cars had diesel engines (diesel cars have higher NO_x emissions than petrol cars), but the actual proportion in the tunnel was not known, and may have been lower. No corresponding emission factor could be derived from the Bell Common measurements although, as noted in Table 21, a negative emission factor was observed for ‘all LDVs’. The calculated emission factors for the Bell Common tunnel are shown for comparison with the Hatfield tunnel in Figure 37. Indeed, there was little difference between the values calculated using the UK emission factors for the two tunnels. On the other hand, the emission factor for large LGVs from the Hatfield tunnel measurements was higher than the UK emission factor (Figure 38). Again, no directly comparable emission factor could be obtained for the Bell Common tunnel, and the UK emission factors for the Hatfield and Bell Common tunnels were similar.

One of the most significant findings of the study was the much larger measured emission factor for heavy-duty vehicles in the Bell Common tunnel (around 17 g vehicle^{-1} km^{-1}) compared with the Hatfield tunnel measurements (around 4-5 g vehicle^{-1} km^{-1}) and the UK emission factors (Figure 39). In addition, the NO_2/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 possible explanation is the difference in road gradient. At Bell Common the magnitude of the gradient effect was estimated using PHEM. The road in the Hatfield tunnel was at level gradient, whereas in the Bell Common tunnel there was an average uphill gradient of around 1.5%, although near the entrance to the tunnel the gradient is closer to 2.5%. Using PHEM, emission factors were calculated for 48 categories of rigid HGV (8 weight bands, 6 levels of emission control), and 36 categories of articulated HGV (6 weight bands, 6 levels of emission control). The maximum speed allowed for HGVs in the model (86 km h^{-1}) was used. The overall ratio between the NO_x emission factor at +2% road gradient and that at level grade was approximately 2 (Boulter *et al*., 2007). When the Hatfield tunnel NO_x emission factors for HGVs were multiplied by a factor of two (*i.e.* introducing a hypothetical 2% uphill gradient in the tunnel), the resulting (weighted) emission factor was 8.3 g vehicle^{-1} km^{-1}. Consequently, although the gradient has an important effect, it does not fully explain the difference between the HGV emission factors in the two tunnels. The HGVs in the Bell Common tunnel may be generally heavier than those in the Hatfield tunnel, although no information was available to allow this to be tested.

Figures 39 to 42 show the NO_x emission factors for different models (NAEI, COPERT III, ARTEMIS (AS) and HBEFA, plus PHEM and MODEM for cars and small LGVs) and vehicle categories in the Hatfield tunnel, calculated for 2005 (when the Hatfield tunnel study began). For cars and small LGVs the predicted NO_x emission factors were all higher than the emission factor derived from the statistical analysis of the Hatfield tunnel data. For LGVs there was a good level of agreement between the model predictions and the Hatfield tunnel measurements (all gave an emission factor 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.

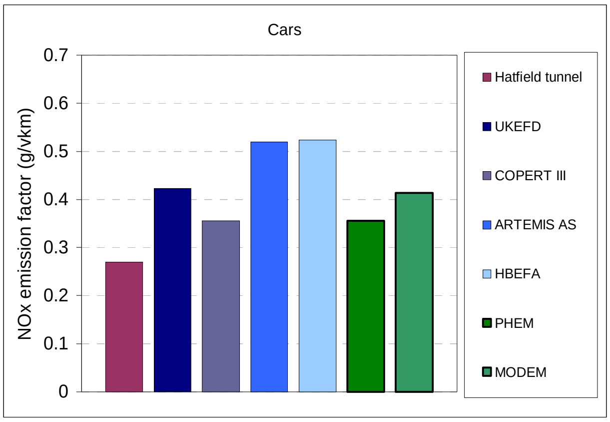


Figure 40: NO_x emission factors for cars in the Hatfield tunnel.

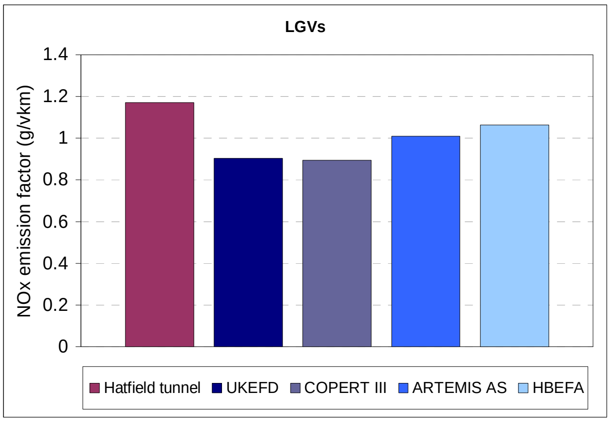


Figure 41: NO_x emission factors for LGVs in the Hatfield tunnel.

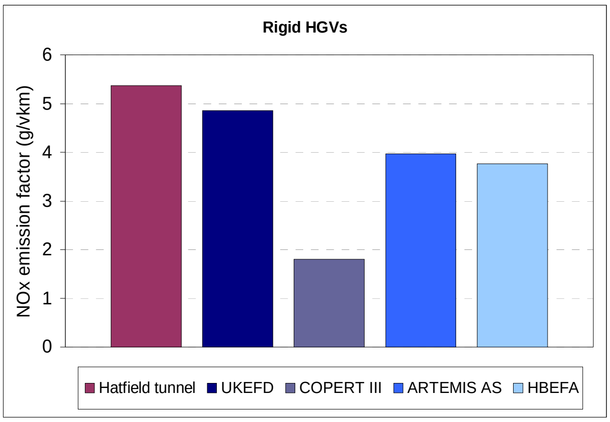


Figure 42: NO_x emission factors for rigid HGVs in the Hatfield tunnel.

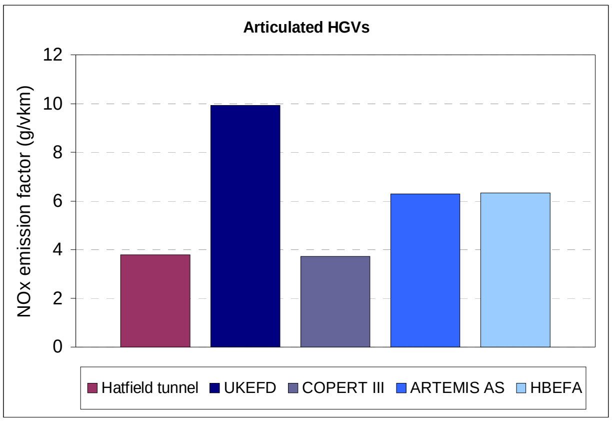


Figure 43: NO_x emission factors for articulated HGVs in the Hatfield tunnel.

5 Review of uncertainty analysis studies

Sensitivity and uncertainty analyses can be used to determine the relative importance of various input parameters when estimating emissions, and to therefore identify which parameters should be given priority in terms of both improving the accuracy of emission estimates and reducing emissions. The analysis of uncertainty is therefore a key approach for improving model reliability.

A number of uncertainty analyses have been conducted on road transport emission factors. Most European studies have been conducted using the COPERT model. Similar exercises have been conducted in the United States using the MOBILE or EMFAC models (Pollack *et al.*, 1999; Frey *et al.*, 1999).

Several sensitivity analyses were conducted in, or in conjunction with, the ARTEMIS project, and an overall review was provided by André *et al.* (2006). This work is summarised below.

A study by SCM/EMITRA (2001) examined the sensitivity of emission estimates to traffic parameters for the road network in Lyon. The EMITRA model combined origin/destination matrices with a traffic assignment model and the COPERT II emission functions. The emission uncertainty for passenger cars was of the order of 20-30% for a variation of 20% in the input parameters, but was found to be higher for heavy-duty vehicles. The main parameters affecting variability in hot exhaust emissions were traffic flow and speed; these two parameters accounted for around 90% of the total variability. Evaporative emissions were dependent upon fuel volatility (30%) and traffic flow/speed (60%). However, the work did not consider the uncertainty in the emission factors themselves.

Duboudin and Crozat (2002) analysed the sources of uncertainty within COPERT III. The analyses were conducted for (i) a single urban road section and (ii) a national inventory for France. The variations in the input (external) and emissions (internal) parameters were defined according to the scientific knowledge. For the urban road study, the most important external parameters were found to be traffic flow, speed, the percentage of distance driven with a cold engine and the petrol:diesel ratio (this list varied according to the pollutant). The main internal parameters were the cold-start excess emission and emissions from non-catalyst petrol cars. The main parameters for VOCs were the emission factors for HDVs, two-wheel vehicles and non-catalyst petrol cars. The analysis revealed an uncertainty on the total emission in the range of ±15% to ±25%, depending on the pollutant (except CO_2). Internal and external parameters appeared to be equally important. In the French national inventory case study, the uncertainties on the total emissions were found to be in the range of ±20% to ±35% for CO and HC, ±13% to ±20% for NO_x and PM, and ±12% for CO_2. When an adjustment for actual fuel sales was applied, this led to an improvement in the overall accuracy. The authors concluded that the uncertainty was linked to internal and input parameters, the most important being (i) traffic volume (ii) speed (iii) the hot emission factors for non-catalyst petrol cars (iv) the cold-start excess emission and (v) for PM and NO_x the diesel car and HDV emission factors.

Within ARTEMIS Kioutsioukis and Tarentola (2003) conducted a literature review and analysed the uncertainty in emission estimates in relation to (i) two national inventories (Italy and France, reference year 2010) and (ii) a single rural road in a tunnel. Again, the COPERT III model was used, and a Monte-Carlo simulation approach was applied.

The results for Italy (2010) showed that:

- The coefficients of variation for *total* annual emission were 22% for VOCs, 15% for NO_x, 26% for PM and 9% for CO_2.
- The most important contributing factors were:
  - VOCs: Average trip length (55%) and emission factors (18%).
  - PM: Diesel share for cars and LDVs (58%), and emission factors (12%).
  - NO_x: Emission factors (48%), and diesel share for cars and LDVs (19%).
  - CO_2: Annual mileage of cars (37%), average trip length (16%), speed during urban driving (12%), and urban driving share of cars (11%).
- The coefficients of variation for *urban* annual emissions were 26% for VOCs, 23% for NO_x, 35% for PM and 20% for CO_2.
- The most important contributing factors in this case were:

  - VOCs: Average trip length (57%) and emission factors (13%).
  - PM: Diesel share for cars and LDVs (45%), urban driving share for HDVs (11%), and average trip length (10%).
  - NO_x: Urban driving share for HDVs (24%), emission factors (16%), diesel share for cars and LDVs (11%), and urban driving share for cars (11%).
  - CO_2: Urban driving share for cars (55%), average trip length (14%), annual mileage of cars (9%).

Similarly, the results for France (2010) showed that:

- The coefficients of variation for the *total* annual emission were 21% for VOCs, 18% for NO_x, 29% for PM and 9% for CO_2.
- The most important contributing factors were:
  - VOCs: Average trip length (53%) and emission factors (24%).
  - PM: Diesel share for cars and LDVs (51%), and emission factors (27%).
  - NO_x: Emission factors (56%), and diesel share for cars and LDVs (27%).
  - CO_2: Annual mileage of cars (45%), average trip length (16%), and speed during urban driving (12%).
- The coefficients of variation for *urban* annual emissions were 28% for VOCs, 20% for NO_x, 35% for PM and 14% for CO_2.
- The most important contributing factors were:
  - VOC: Average trip length (57%) and emission factors (19%)
  - PM: Diesel share for cars and LDVs (53%), emission factors (21%), and average trip length (16%)
  - NO_x: Emission factors (53%) and diesel share for cars and LDVs (32%)
  - CO_2: Annual mileage of cars (22%), average trip length (21%) and urban driving share for cars (19%).

At the national level reliable estimates of the average trip length (used to compute the cold-start emission), the emission factors, the diesel share for cars and light-duty vehicles and the annual mileage of passenger cars are critical for the accurate estimation of emissions. The emission factors played a major role for NO_x and a secondary role for VOC and PM, but were less important for CO_2.

The uncertainty analysis for the single road of the results gave the following coefficients of variation: 8.6% for VOC, 5.8% for NO_x, 6.9% for PM and 2.1% for CO_2. The coefficients were substantially lower than those for the country-level estimates due to the fixing of several sources of uncertainty (*e.g.* the driving pattern). The speed and the load factor for HDVs were generally found to be the most important parameters, and accounted for up to 70-80% of the variability in emissions (HDVs represented 55% of the total number of vehicles in the tunnel traffic).

For the UK situation Cloke *et al.* (2001) quantified the effects of the following parameters on emission estimates: (i) vehicle distributions and categorisation (ii) speed (iii) vehicle age (iv) trip length and (v) ambient temperature. The results demonstrated the importance of speed, HDV weight, and car age/legislation category. The authors recommended that these parameters (in particular speed and fleet composition) should be quantified more accurately for local-scale studies.

These studies have shown that uncertainty in emission models is linked to internal and input parameters. They have highlighted the importance of accurate data for several traffic parameters, notably traffic flow, annual mileage and speed, which are generally more important than the actual unit emission factors. However, accurate hot emission factors for non-catalyst cars, cold-start emission factors, and diesel car and HDV emission factors (for PM and NO_x) are still important. This raises the question of the quality of emission estimates, as most effort is usually dedicated to the measurement and modelling of emissions, whilst the quality of the necessary traffic data is rarely considered (André *et al.*, 2006). In future, a statistical examination should be made of the uncertainties inherent in each stage of the emission modelling procedure.

6 Summary

6.1 Background

For hot exhaust emissions the current UK emissions factors for regulated pollutants, and for some non-regulated pollutants, are defined as a function of average vehicle speed over a trip. This may not be the best approach in some circumstances, and other means of characterising vehicle emission performance may be more accurate.

Models for estimating hot exhaust emissions have bee reviewed. The average-speed method used in the NAEI (UKEFD) has been described and potential limitations of the method have been highlighted. 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.

6.2 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 NAEI was taken to represent the base case with which the following were compared:

- COPERT III - average speed model
- ARTEMIS - average speed model
- ARTEMIS - traffic situation model
- HBEFA - traffic situation model
- VERSIT+ - multiple regression model

The instantaneous models MODEM and PHEM were also included in the comparisons, although these types of model are not suitable for use in large-scale emission inventories.

Groups of driving patterns were used as the input to the various models. The driving patterns were selected from a large TRL database, 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 currently 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 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 CO_2 from both. With regards the magnitude of the emissions estimates, the best agreements between the models appeared to be for NO_x and CO_2. 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.

6.3 Evaluation of model and emission factor accuracy

Four types of comparison were used in an attempt to determine the accuracy of the predictions of different models:

- Comparisons with on-board emission measurements.
- Comparisons with remote sensing measurements.
- Comparisons with the results from the inversion of an air pollution model.
- Comparisons with the results from measurements in road tunnels.

Comparisons with on-board measurements

A single Euro 3 petrol car was fitted 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 CO_2, though in this case the average-speed functions in the NAEI predicted higher emissions than were measured. The results from this vehicle indicated that 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.

Comparisons with 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 using remote sensing emission measurements in Sweden. 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. 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.

Comparisons with the results from the inversion of an air pollution model

The air pollution prediction algorithms in the DMRB Screening Method were inverted to estimate emission factors for vehicles on Marylebone Road, London. Separate emission factors (CO, NO_x, $PM_{2.5}$) 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

Comparisons with the results from measurements in road 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. Continuous measurements were undertaken of NO, NO_2 and O_3 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 heavy-duty vehicles 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 NO_2/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 HGV 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 statistical analysis of 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}). Any good agreement between the models, at least for cars and LGVs, is probably due in part to large amounts of data sharing, with the same vehicle test results often being used in different models.

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.

7 Conclusions and recommendations for NAEI

The conclusions from this work are as follows:

1. Several specific models for estimating hot exhaust emissions could be used in the NAEI, based on aspects such as availability, cost, coverage of pollutants and vehicle categories, robustness, and ease of use. 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 traffic situation model would require considerably more work, as the activity data would have to be reconfigured and transport statistics would have to be analysed differently.
2. Various average-speed and traffic situation models were compared with the NAEI model, including COPERT III, ARTEMIS and HBEFA. The instantaneous models MODEM and PHEM were also included in the comparisons, although as stated earlier these types of model are not suitable for use in large-scale emission inventories on account of the large amount of input data required. 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 CO_2. For CO and HC, most of the comparisons showed a poorer agreement, with PM being intermediate.
3. Four types of assessment were considered in an attempt to determine the accuracy of the predictions of different models. These assessments - some of which relied upon the analysis of data, and others on information available in the literature - 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. 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.
4. Notwithstanding the previous conclusion, the results of the assessments indicated 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. However, 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.
5. 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).
6. 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.

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Appendix A: Abbreviations and terms used in the Task Reports

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

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

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

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

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

Appendix B: Multiple regression analysis

Carbon monoxide

The output shows the results of fitting a multiple linear regression model to describe the relationship between CO and two independent variables. The equation of the fitted model is:

$$\mathit{CO} = 339.798 + 7.03689 * \mathit{LDV} + 1.7784 * \mathit{HDV}$$

Table D1: Multiple regression analysis for CO.

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant	339.8	641.4	0.529774	0.596
LDV	7.04	0.25	27.6704	0.000
HDV	1.78	1.01	1.75854	0.079

`

Table D2: ANOVA for CO.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	8.61804E10	2	4.30902E10	519.16	0.0000
Residual	1.67495E11	2018	8.30005E7		
Total (Corr.)	2.53675E11	2020			

The R-Squared statistic indicates that the model as fitted explains 34% of the variability in CO.

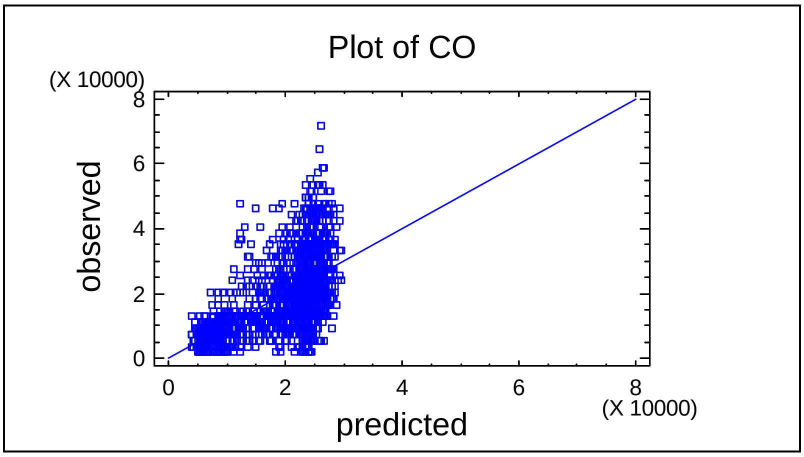

Figure D1: Observed vs predicted traffic emissions for CO.

Nitrogen oxides

The output shows the results of fitting a multiple linear regression model to describe the relationship between NO$_x$ and two independent variables. The equation of the fitted model is:

$$\mathit{NOx} = 567.161 + 6.99127 * \mathit{HDV} + 0.996246 * \mathit{LDV}$$

Table D3: Multiple regression analysis for NO_x.

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant	567.2	214.1	2.65	0.0081
LDV	0.996	0.089	11.16	0.0000
HDV	6.99	0.35	20.15	0.0000

Table D4: ANOVA for NO_x.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	6.92022E9	2	3.46011E9	536.81	0.0000
Residual	9.03686E9	1402	6.44569E6		
Total (Corr.)	1.59571E10	1404			

The R-Squared statistic indicates that the model as fitted explains 44% of the variability in NO_x.

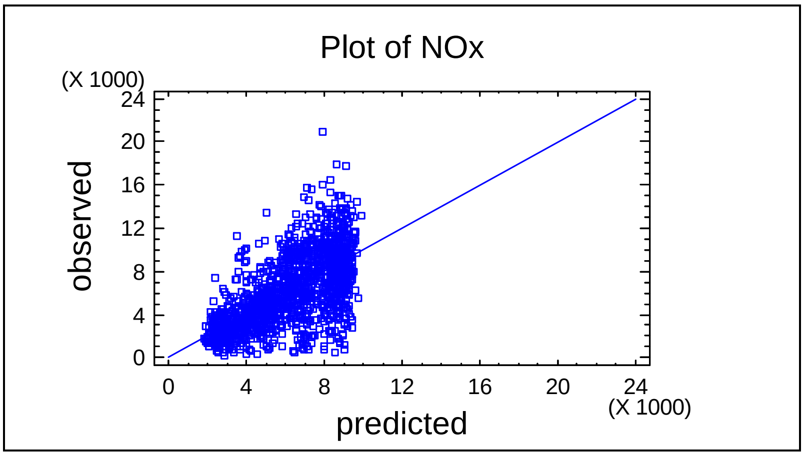

Figure D2: Observed vs predicted traffic emissions for NO_x.

$PM_{2.5}$

The output shows the results of fitting a multiple linear regression model to describe the relationship between $PM_{2.5}$ and two independent variables. The equation of the fitted model is:

PM2.5 = 13.3358 + 0.249838 * HDV + 0.0351035 * LDV

Table D5: Multiple regression analysis for $PM_{2.5}$.

Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant	13.3358	6.4681	2.06177	0.0392
LDV	0.0351035	0.0026503	13.2451	0.0000
HDV	0.249838	0.0103206	24.2077	0.0000

Table D6: ANOVA for $PM_{2.5}$.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1.01311E7	2	5.06554E6	733.16	0.0000
Residual	1.16559E7	1687	6909.23		
Total (Corr.)	2.17869E7	1689			

The R-Squared statistic indicates that the model as fitted explains 46.5% of the variability in NO_x.

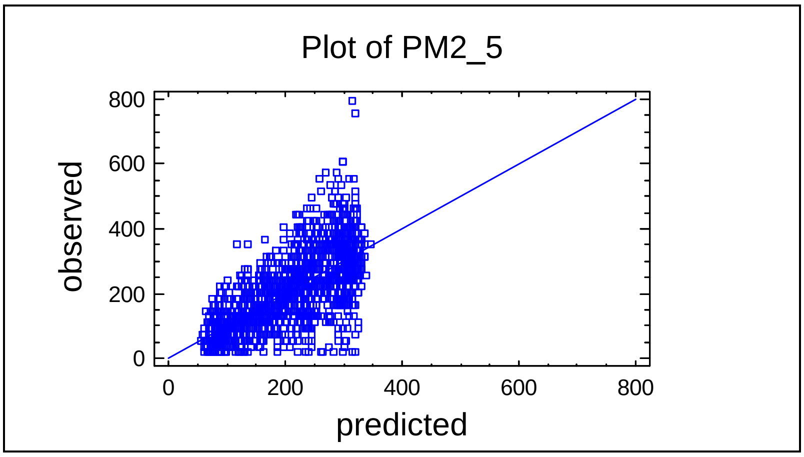

Figure D3: Observed vs predicted traffic emissions for $PM_{2.5}$.

Emission factors 2009: Report 2 – a review of the average-speed approach for estimating hot exhaust emissions systems

TRL was commissioned by the Department for Transport to review the approach used in the National Atmospheric Emissions Inventory (NAEI) for estimating emissions from road vehicles, and to propose new methodologies. This Report reviews the use of average vehicle speed (as used in the NAEI) to characterise exhaust emissions. Several alternative models for estimating emissions could be used in the NAEI. Some of these essentially use the same modelling approach as the NAEI, and could therefore be introduced with only minor changes to the model inputs. Others would require considerably more work, as the activity data would have to be reconfigured and transport statistics would have to be analysed differently. Various models were compared with the NAEI model. Generally, there was a very good agreement between the emission factors in the NAEI and those in 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. 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. Nevertheless, the results indicate that the current UK emission factors probably provide a reasonably accurate characterisation of total emissions from road transport. However, the emission factors for 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. The Report concludes that there is 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).

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