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Emission factors 2009: Report 1 – a review of methods for determining hot exhaust emission factors for road vehicles

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

TRL Limited

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Emission factors 2009: Report 1 – a review of methods for determining hot exhaust emission factors for road vehicles

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

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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 (these are described in separate Reports). This Report reviews the experimental methods used to determine emission factors, and provides recommendations for the future development of emission factors in the UK. It covers only 'hot' exhaust emissions which occur when the engine and any after-treatment devices have reached their full operational temperatures, and includes two main elements: (i) an evaluation of the driving cycles used in emission tests and (ii) a review of the parameters recorded during emission tests. A distinction is also made between the improvement of the emission factors in the 2002 UK Emission Factor Database (UKEFD) and the requirements with respect to future tests.

For cars, the assessment indicated that the driving cycles in the UKEFD adequately cover the range of driving characteristics observed in the real world. However, a small number of UKEFD driving cycles appear to have average accelerations which are outside the range of real-world conditions. Furthermore, the Warren Spring Laboratory (WSL) cycles - which are routinely used for emission tests in the UK - do not appear to reproduce the aggressiveness of driving for cars and light goods vehicles (LGVs), and do not cover the highest speeds encountered on the road. A more representative set of driving cycles should therefore be considered for future testing. Alternatively, the WSL cycles could be retained, but supplemented with some high-speed cycles, and cycles which have higher average accelerations and decelerations.

For LGVs the database of real-world driving patterns is more limited. However, the cycles used in the current UKEFD appear to cover the range of driving characteristics which are likely to be encountered. However, as with cars some UKEFD cycles may have average accelerations which are not realistic for the UK. This also needs to be investigated further.

In the case of HGVs, some of the low-speed UKEFD driving cycles have relatively high accelerations which are not apparent in the real-world driving patterns. Some of the UKEFD cycles have more rapid decelerations than the real-world driving patterns. The FiGE cycle - which is commonly used to test heavy-duty vehicles - does not cover low average speeds and does not reflect the speeds of older, unrestricted vehicles. The higher-speed FiGE cycles (suburban and motorway) also appear to have low average accelerations and have less rapid decelerations than the real-world driving patterns. Again, a more representative set of driving cycles should be considered for future testing.

Urban buses operate at relatively low speeds, and may be unable to attain the higher speeds required for some driving cycles. Coaches, on the other hand, are likely to operate at higher motorway speeds. Urban buses and coaches should therefore be treated separately when deriving emission factors, and more representative driving cycles for these vehicle classes should be used in the derivation of the future UK emission factors.

The use of generic driving cycle in emission tests (as opposed to vehicle-specific cycles) could lead to errors in emission estimations. Although it would increase the complexity of the test procedure, taking into account vehicle performance by the use of specific driving cycles would lead to an improvement in the quality of emission estimates. An alternative may be to develop a test cycle that could be broken down into a large number of sub-cycles, and the emissions over each sub-cycle could be calculated. This would allow a limited number of test cycles to yield a larger number of data points.

Although continuous emission measurements can aid the understanding of different effects, there is an additional cost. As emission models are constructed primarily using bag samples there appears to be little justification for routinely including continuous emission measurements in the tests used for emission factor development. This recommendation does not apply to *ad hoc* tests for the evaluation of technical and/or policy measures, for which continuous measurements may be beneficial.

When compiling an emission factor database, adjustment factors should be applied in order to standardise the data for the gear-shift strategy, the vehicle mileage, the ambient temperature and the ambient humidity.

Emission measurements are required for a wider variety of two-wheel vehicles and their associated operation, particularly for the most modern vehicles.

1 Introduction

1.1 Background

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

TRL Limited has been commissioned by the Department for Transport (DfT) to review the methodology currently used in the NAEI to estimate emissions of air pollutants from road vehicles.

In the measurement and modelling of vehicle emissions, various abbreviations and terms are used to describe the concepts and activities involved. Appendix A provides a list of abbreviations and a glossary which explains how specific terms are used in the context of this Report (and others produced in the project).

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

1.2 Potential weaknesses in the NAEI model

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 NAEI road transport methodology is summarised in Appendix B.

Recent UK and European Union (EU) research projects on road transport emission modelling have identified potential weaknesses in the types of methodology used in the UK. There are also some areas of the NAEI's road transport model which are based on rather old data and are due to be updated. Furthermore, concerns have been expressed about so-called 'off-cycle'[4] vehicle emissions performance, and how well this is covered by the current methods for determining emission factors. It is therefore appropriate to review how well the driving cycles used in emission tests represent the full range of on-road driving conditions. These concerns are discussed in more depth in the following paragraphs, in which model weaknesses are identified in relation to the various types of emission source associated with road vehicles.

1.2.1 Hot exhaust emissions (the UKEFD)

'Hot' exhaust emissions are produced by a vehicle when its engine and exhaust after-treatment system are at their normal operational temperatures. The temperature of engine coolant during normal operation is typically between around 70^{o}C and 90^{o}C, whereas the temperature of the exhaust system reaches several hundred degrees centigrade. Hot exhaust emission factors for various categories of vehicle and pollutant are given in the UK Emission Factor Database (UKEFD). These emission factors are used in the NAEI. During 2002, an updated version of the database, containing emission functions for carbon monoxide (CO), total hydrocarbons (HC), oxides of nitrogen (NO_x), PM_{10}[5], benzene, 1,3-butadiene and carbon dioxide (CO_2), and functions describing fuel consumption, was prepared by TRL and NETCEN. The database included existing

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

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

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

[4] The term 'off-cycle' relates to vehicle operation and emission behaviour which is not covered in legislative tests.

[5] PM_{10} = particulate matter with an aerodynamic diameter of less than 10 μm.

measurements from an earlier version, data from the EC MEET[6] 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 identical to those given in the procedure for air pollution estimation in Volume 11 of the Design Manual for Roads and Bridges (DMRB) (Highways Agency *et al*., 2007). The 2002 UKEFD is still used as the basis for a wide range of emission and air pollution modelling studies in the UK.

However, a number of specific weaknesses in the 2002 UK database were identified in a TRL Report (Boulter *et al*., 2005), including the following:

- *Robustness of the existing emissions data*
  - There are very few test results for Euro 3 cars.
  - The measurements on Euro 2 LGVs are very limited.
  - The measurements on Euro I and Euro II HGVs and buses are limited.
  - There is little information on emissions from motorcycles.

- *Coverage of vehicle types and fuel types*
  - There are no emission measurements for Euro 4 cars.
  - There are no emission measurements for Euro 3 and Euro 4 LGVs, and Euro III/IV HGVs and buses.
  - There are no emission functions for vehicles running on fuels other than petrol or diesel (*e.g.* CNG, LPG), and for certain engine technologies (*e.g.* petrol direct-injection).
  - There are no emission functions for post-Euro 4/IV vehicles of all types.
  - No information is provided on the effects of specific after-treatment technologies, such as particulate traps, selective catalytic reduction, *etc.*

- *Coverage of pollutants*

  Only a small number of unregulated compounds are covered, with the emission functions being based on very limited measurements and various assumptions.

- *Coverage of operational conditions*
  - The emission functions do not include the effects of using ancillary equipment, variations in vehicle load, or gradient effects.
  - There are few emission measurements for very low speeds (*i.e*. less than 5 km/h) and very high speeds (*i.e*. greater than 130 km/h), as well as for idling.

It should also be stated that there is an absence of detailed methods for taking fuel properties (‘fuel quality’) and lubricant effects 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.

There are also considered to be a number of limitations associated with the average-speed modelling approach used in the NAEI. These will be addressed in detail later in the project, although some of the potential problems are briefly introduced in Chapter 2.

1.2.2 Cold-start emissions

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

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

1.2.3 Evaporative emissions

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

1.2.4 Non-exhaust PM emissions

There are currently no EU regulations specifically designed to control non-exhaust emissions of particulate matter (PM) from road vehicles, such as those arising from tyre wear, brake wear, road surface wear and the resuspension of material previously deposited on the road surface. As exhaust emission-control technology improves and traffic levels increase, the proportion of total PM emissions originating from uncontrolled non-exhaust sources will increase. Furthermore, the data relating to the emission rates, physical properties, chemical characteristics, and health impacts of non-exhaust particles are highly uncertain. However, non-exhaust emissions were outside the scope of this project.

1.3 Project objectives

The overall purpose of this project is to propose complete methodologies for modelling UK road transport emissions. The project includes an extensive and detailed review of the current methodology. Specific aims include the identification of approaches which could improve the quality of the model and areas where existing methodologies give good quality estimates and should be retained.

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

- Task 1: Reviewing the methods used to measure hot exhaust emission factors, including test cycles and data collection methods (this Report).
- Task 2: Reviewing the use of average vehicle speed to characterise emissions (Barlow and Boulter, 2009).
- Task 3: Development of new emission factors for regulated and non-regulated pollutants (Boulter *et al.*, 2009a).
- 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.*, 2009b).

1.4 Report structure

This Report presents the findings of Task 1. The overall aim of this Task was to review the experimental methods used to determine emission factors, and to provide recommendations for the future development of emission factors in the UK.

The Report only covers hot exhaust emissions, and includes two main elements: (i) an evaluation of the driving cycles used in emission tests and (ii) a review of the parameters recorded during emission tests. The Report is structured according to these two elements, with driving cycles being covered in Chapter 2 and test parameters being described in Chapter 3. Chapter 4 includes a summary of the findings, the conclusions, and recommendations for future emission factor development. A distinction is made between the improvement of the current emission factors in the UKEFD and the requirements with respect to future tests. For the former, large numbers of test results are available for some vehicle categories, and the tests cover a wide range of vehicle operating conditions. In the case of future tests, a simpler range of test conditions needs to be defined to allow the representative emission factors to be determined in a cost-effective manner.

2 Evaluation of driving cycles

2.1 Background

The main objective of Task 1 was to review the methods used to derive the hot exhaust emission factors in the UKEFD. This requires that some consideration be given to the emission measurement process, an important aspect of which is the definition and application of driving cycles to represent different types of vehicle operation. The central role of the driving cycle in emission measurement and modelling is discussed in more detail below. The method by which the review was conducted and the results which were obtained are described in Sections 2.2 and 2.3 respectively.

2.1.1 The use of driving cycles in the measurement of emissions

Various atmospheric pollutants are emitted from road vehicles as a result of fuel combustion and other processes. Exhaust emissions of CO, HC, NO_x and PM are regulated at type approval by EU Directives, as are evaporative emissions of VOCs. Various unregulated gaseous pollutants are also emitted, but these have generally been characterised in less detail (with the exception of CO_2).

Emission tests are required at type approval for all new light-duty vehicle models and for the engines used in heavy-duty vehicles. Exhaust emissions are inherently rather variable, and so the best way to ensure that an emission test is reproducible is to perform it under standardised laboratory conditions. The procedures for the collection and analysis of pollutants are specified in the legislation. Light-duty vehicles are tested using a power-absorbing chassis dynamometer, whereas heavy-duty engines are operated on a test bed. For research projects and emission factor development, vehicle-based measurements have also been conducted for heavy-duty vehicles. Indeed, the time and cost involved in setting up an engine on a test bed can be far greater than the time and cost associated with the actual test itself, and therefore full-vehicle tests are often more practical.

In tests conducted using a chassis dynamometer the vehicle drive wheels are placed in contact with rollers which can be adjusted to simulate frictional and aerodynamic resistance. The sampling of exhaust emissions is then performed as the vehicle progresses through a pre-defined driving cycle. A driving cycle is a fixed schedule of vehicle operation, and is usually characterised in terms of vehicle speed and gear selection as a function of time. A trained driver is employed to follow the driving cycle on the chassis dynamometer and a ‘driver’s aid’ is provided to ensure that the driven cycle is as close as possible (*i.e.* within stated tolerances) to the defined cycle.

Emission levels are dependent upon many parameters, including vehicle-related factors such as model, size, fuel type, technology level and mileage, and operational factors such as speed, acceleration, gear selection and road gradient. Not surprisingly, therefore, different driving cycles have been developed for different types of vehicle and different types of operation. Driving cycles may also be used for a variety of purposes other than emissions measurement, such as testing engine or drive-train durability, and may be used on a test track rather than in the laboratory.

Depending on the character of the speed and engine load changes, driving cycles can be broadly divided into two categories: ‘steady-state’ and ‘transient’. A steady-state cycle is a sequence of constant engine speed modes and constant load modes. Such cycles can be used to test vehicles, but are mainly used for the testing of heavy-duty engines. In the case of transient cycles, the vehicle speed and engine load are changing continuously. Three types of transient driving cycle are shown in Figure 1, 2 and 3. Figure 1 depicts a driving cycle which has been specifically designed to fit a particular requirement - the ‘New European Driving Cycle’ (NEDC), which is used for type approval of light-duty vehicles in the EU. It is clearly a highly stylised cycle with periods of constant acceleration, deceleration and speed. Figure 2 shows an example of a driving cycle which is based directly upon real-world data collected from vehicles operated on the road. In some cases a real-world cycle might be derived from the actual data from one trip, whereas in other cases segments of data from a number of trips may be amalgamated to produce a representative cycle. There is clear contrast between the real-world cycle and the legislative cycle; real-world cycles generally have much more transient operation than stylised cycles such as the NEDC, which bears little relation to driving patterns on the road. Figure 3 shows a ‘pseudo-steady-state’ driving cycle (EMPA T115), which represents an attempt to maintain a constant speed in free-flowing traffic. When trying to maintain a constant speed, variations in speed occur for a number of reasons, including subtle changes in throttle position, direction of travel, and gradient. Driving cycles are also often divided into sub-cycles which represent different aspects of operation. For example, the NEDC is divided into an 'urban' part and a 'highway' part, and separate emission measurements are usually available for the sub-cycles.

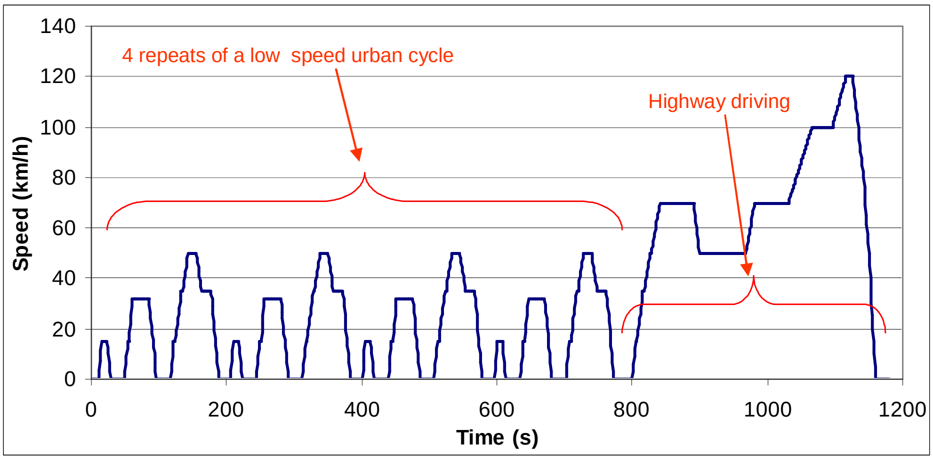

Figure 1: An example of a stylised transient cycle (NEDC).

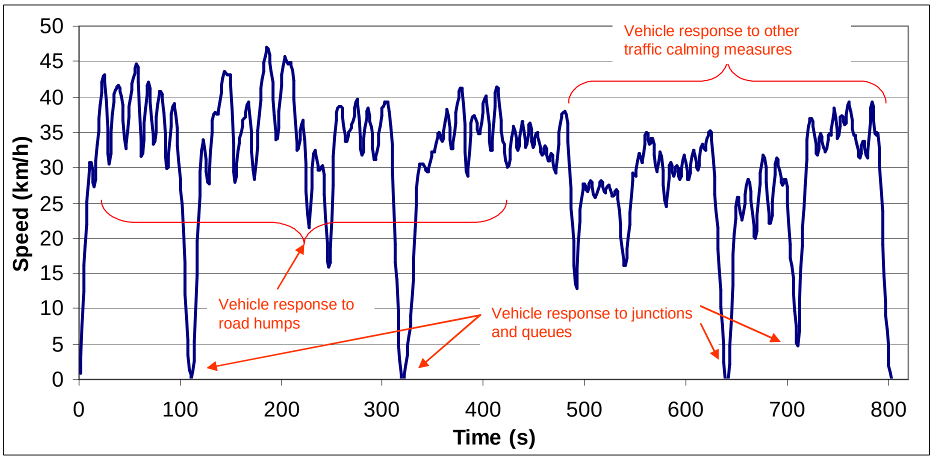

Figure 2: An example of a real-world transient cycle (traffic calming cycle for cars).

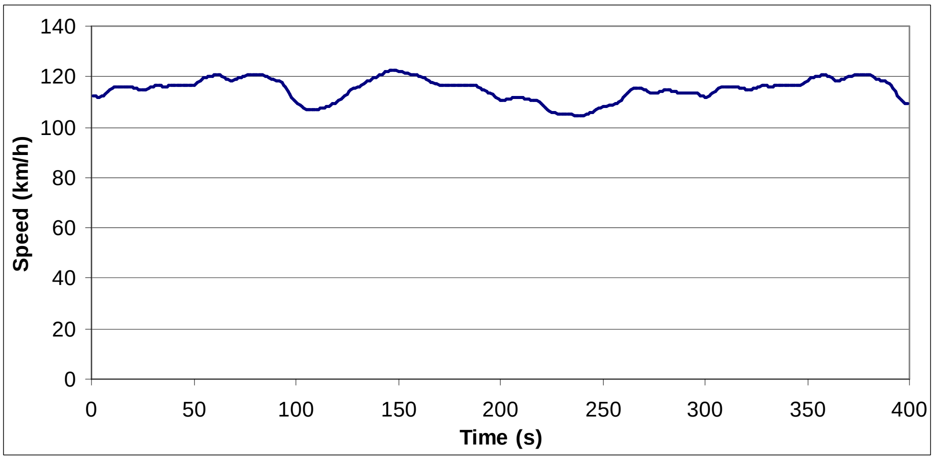

Figure 3: An example of a pseudo-steady-state cycle (EMPA T115).

2.1.2 The importance of driving cycles in emission modelling

All emission models must take account of the various factors affecting emissions, although the manner in which they do so, and the level of detail involved, can differ substantially from model to model. One of the commonest approaches - and the one used in the UKEFD - is 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 usually stated in grammes per vehicle-kilometre (g $vehicle^{-1}$ km^{-1}). A continuous (typically polynomial) function is then fitted to the emission factors measured for several vehicles over a range of driving cycles, with each cycle representing a specific type of driving. Average-speed emission functions for road vehicles are widely applied in regional and national inventories, but are also currently used in a large proportion of local air pollution prediction models. The European Environment Agency's COPERT[7] model is probably the most widely-used model of this type in Europe.

There are now considered to be a number of limitations associated with average-speed models, one of which is the inability to account for the ranges of vehicle operation and emission behaviour which can be observed for a given average speed. This is especially relevant in the case of modern catalyst-equipped petrol vehicles, for which 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. One alternative to average-speed modelling is an approach which relates discrete emission factors to specific 'traffic situations' (*e.g.* INFRAS, 2004). Such an approach is used for national inventories and local applications in Austria, Germany and Switzerland. As before, the emission factors are derived using driving cycles, and in this case the driving cycles clearly need to be representative of the traffic situations they describe. How this is determined, in a way which is meaningful in terms of emissions, is rather problematic.

With respect to the issue of representativity posed by average-speed models and traffic situation models, the concept of driving cycle 'dynamics' has become useful for emission model developers (*e.g.* Sturm *et al*., 1998). In qualitative terms, cycle dynamics might be thought of as the 'aggressiveness' of driving, or the extent of transient operation in a driving pattern. In order to quantify dynamics, various statistical descriptors of driving cycles have been used, and researchers have attempted to understand the links between such descriptors and emissions. However, as the information on vehicle operation available to model users (and often model developers) has tended to be very limited, and almost invariably speed-based, interest has inevitably focussed on parameters which describe speed variation in some way. For example, some of the more useful parameters appear to be relative positive acceleration (Ericsson, 2000) and average positive acceleration (Osses *et al*., 2002). These descriptors, and others, will be discussed later in the Report.

2.1.3 Driving cycles used in the UKEFD

A total of 70 different driving cycles (including sub-cycles) were used to derive the functions for cars, LGVs, HGVs and buses in the 2002 UKEFD. These cycles are listed in Table 1, and are grouped broadly according to their origin (programme or organisation). The full list of vehicle categories included in the UKEFD is given in Appendix B. For cars the European legislative driving cycles were not used during the derivation of average-speed functions in the UKEFD, as the emphasis was placed upon emissions data measured over real-world cycles. Hence, only 'off-cycle' driving conditions (*i.e.* those not covered by legislative test procedures) were included. The emission factors for motorcycles in the 2002 UKEFD were developed some time ago, and no records are available of the driving cycles used.

A number of the driving cycles used in the development of the 2002 UKEFD are now also rather old. For example, the 'congested traffic' cycle developed by the Warren Spring Laboratory ('WSL CT') pre-dates its closure in 1994, and the MODEM cycles were developed in the early 1990s during the European Commission Fourth Framework DRIVE project (André *et al.*, 1991). Many of the cycles used in the UKEFD were also developed outside the UK. Furthermore, one of the most important and widely-used driving cycles to have emerged in recent years – the ARTEMIS driving cycle (see Chapter 3), was developed after the UKEFD was released. There is therefore some uncertainty relating to how well the cycles in the UKEFD reflect current driving behaviour in the UK, as well as the types of driving expected in the future. Consequently, it was considered appropriate to review how well the emissions factor test cycles represent the range of on-road driving conditions in the UK, and to suggest how the methodology might be improved.

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

Table 1: Driving cycles used in derivation of the 2002 UKEFD.

Group and driving cycle	Description	Vehicle category [a]
FiGE (Simulated ETC)		
FiGE Urban	Urban	HGV/Bus/ LGV
FiGE Suburban	Suburban	HGV/Bus/ LGV
FiGE Motorway	Motorway	HGV/Bus/ LGV
FiGE Total	Overall	HGV/Bus/ LGV
M25 High-speed cycles		
M25 High-speed	M25 driving cycle	Car
Millbrook heavy-duty truck		
MHDT-Urban	Urban	HGV
MHDT-Sub	Suburban	HGV
MHDT-Mot	Motorway	HGV
MHDT-Total	Overall	HGV
Millbrook/London Transport bus cycles [b]		
MLTBus-IL	Inner London	HGV
MLTBus-OL	Outer London	HGV
MLTBus-Total	Overall	HGV
TRL-WSL [c]		
TRL-WSL Mot113	Motorway cycle 113 km h^{-1}	Car
TRL-WSL Mot90	Motorway cycle 90 km h^{-1}	Car
TRL-WSL Rural	Rural road cycle	Car
TRL-WSL Sub	Suburban road cycle	Car
TRL-WSL Urb	Urban road cycle	Car
WSL CT	Congested traffic	Car/LGV
TRRL		
TRRL 1.1	Real-world driving cycle	Car/LGV
TRRL 1.2	Real-world driving cycle	Car/LGV
TRRL 1.3	Real-world driving cycle	Car/LGV
TRRL 1.4	Real-world driving cycle	Car/LGV
TRRL 2.1	Real-world driving cycle	Car/LGV
TRRL 2.2	Real-world driving cycle	Car/LGV
TRRL 2.3	Real-world driving cycle	Car/LGV
TRRL 2.4	Real-world driving cycle	Car/LGV
WSL Road (on-board emission measurements)		
WSL Mot113	Motorway test 113 km h^{-1}	Car/LGV
WSL Mot90	Motorway test 90 km h^{-1}	Car/LGV
WSL Mot70	Motorway test 70 km h^{-1}	LGV
WSL Suburban	Suburban test	Car/LGV
WSL Urban	Urban test	Car/LGV
WSL Rural	Rural test	Car/LGV
MODEM cycles		
MODEM 1	Cycle 1	Car
MODEM 2	Cycle 2	Car
MODEM 3	Cycle 3	Car
MODEM 4	Cycle 4	Car
MODEM 5	Cycle 5	Car
MODEM 6	Cycle 6	Car
MODEM 7	Cycle 7	Car
MODEM 567	Cycles 5, 6 & 7	Car
MODEM 8	Cycle 8	Car
MODEM 9	Cycle 9	Car
MODEM 10	Cycle 10	Car
MODEM 11	Cycle 11	Car
MODEM 12	Cycle 12	Car
MODEM 13	Cycle 13	Car
MODEM 14	Cycle 14	Car
MEET and EC/IM cycles		
bab1000	TÜV full Autobahn cycle	Car
bab436	TÜV autobahn sub-cycle	Car/LGV
bab736	TÜV autobahn sub-cycle	Car/LGV
mUFF	MODEM Free-flow urban	Car/LGV
mM	MODEM motorway	Car/LGV
mR	MODEM road	Car/LGV
route2	INRETS rural cycle	Car
uflui2	INRETS fluid urban cycle	Car
ulent2	INRETS slow urban cycle	Car
cgv	INRETS cycle	Car
mShort	INRETS short cycle	Car
Highway	US UWFET cycle	Car/LGV
T80	Motorway test 80 km h^{-1}	Car/LGV
T100	Motorway test 100 km h^{-1}	Car/LGV
T115	Motorway test 115 km h^{-1}	Car
T120	Motorway test 120 km h^{-1}	Car/LGV
T130	Motorway test 130 km h^{-1}	Car/LGV
US legislative		
FTP-75(2)	FTP bag 2	Car/LGV
FTP-75(3)	FTP bag 3	Car/LGV
IM240	Inspection & maintenance	Car/LGV
Millbrook/Westminster Dustcart		
MWDust-Com	Commercial collection	HGV
MWDust-Depot	From depot	HGV
MWDust-Dom	Domestic collection	HGV

a HGV = heavy goods vehicle.
b Emission tests conducted on a single HGV rather than buses.
c Developed by TRL after the closure of the Warren Spring Laboratory.

2.2 Method

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

(i) The compilation of a driving cycle 'Reference Book' in order to characterise driving cycles in a systematic manner for use within the project.

(ii) A quantitative investigation of the extent to which the cycles currently used in the UKEFD and the cycles commonly used in recent DfT emission test programmes represent the range of driving conditions experienced on UK roads.

2.2.1 Compilation of a driving cycle Reference Book

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

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

In some cases adaptations to cycles (or the way in which the tests were conducted) may also have been made, thus increasing the numbers still further. In Europe alone, hundreds, if not thousands, of different driving cycles have been used. However, the vast majority of emission tests have been conducted over a relatively small number of these cycles - most notably the driving cycles defined in legislation.

It appears that there is no single document which comprehensively describes all these cycles, although some efforts have been made to bring together the various legislative cycles used in different countries (*e.g.* CONCAWE, 2004; DieselNet, 2006). The first activity in Task 1 was therefore the compilation of a Reference Book of driving cycles (Barlow *et al*., 2009).

The collation and characterisation of available driving cycles in a single document potentially involved an enormous amount of work, and for practical purposes the scope of the Reference Book therefore had to be limited according to certain criteria. In fact, the Reference Book focused exclusively on *transient, vehicle-based driving cycles used in the laboratory to measure exhaust emissions*. Furthermore, the emphasis was placed upon those driving cycles which could be relevant to the UK.

Descriptions of 256 driving cycles were produced in a standardised format. An effort was made to compile a list of driving cycles which was as comprehensive as possible, although there are likely to be many omissions. There is an intention to revise the Reference Book at a later date in order to increase the number of cycles included and the depth of coverage for each cycle. The Reference Book was designed primarily for use by TRL within the DfT project, although it is also hoped that it will be a useful source of information for other researchers and practitioners in the fields of vehicle emissions and air pollution.

As noted in the introduction, average speed is not necessarily the best indicator of emissions for all types of vehicle, and the characteristics of driving patterns need to be assessed in a way which ought to be meaningful in terms of emissions. Consequently, the representativeness of the driving cycles used in the NAEI was assessed in terms of a much wider range of driving cycle parameters (*i.e.* descriptors of cycle dynamics). This assessment was conducted using an existing tool - the *Art.Kinema* program - which was produced as part of the ARTEMIS project (De Haan and Keller, 2003). *Art.Kinema* computes a wide range of descriptive parameters (more than 30) for a user-defined driving cycle. These 'kinematic' parameters are listed in Table 2, and their definitions are provided in Appendix C.

Table 2: Kinematic parameters computed by the *Art.Kinema* program.

Group	Parameter	Units	Group	Parameter	Units
Distance-related	Total distance	m	Acceleration-related	Average negative accel.	$m\ s^{-2}$
Time-related	Total time	s		Standard deviation of accel.	$m\ s^{-2}$
	Driving time	s		Standard dev. of positive accel.	$m\ s^{-2}$
	Cruising time	s		Accel.: 75th - 25th percentile	$m\ s^{-2}$
	Drive time spent accelerating	s		Number of accelerations	-
	Drive time spent decelerating	s		Number of accel. per km	km^{-1}
	Time spent braking	s	Stop-related	Number of stops	-
	Standing time	s		Number of stops per km	km^{-1}
	% of time driving	%		Average stop duration	s
	% of cruising	%		Average dist. between stops	m
	% of time accelerating	%	Dynamics-related	Relative positive accel.	$m\ s^{-2}$
	% of time decelerating	%		Positive kinetic energy	$m\ s^{-2}$
	% of time braking	%		Relative positive speed	-
	% of time standing	%		Relative real speed	-
Speed related	Average trip speed	$km\ h^{-1}$		Relative square speed RSS	$m\ s^{-1}$
	Average driving speed	$km\ h^{-1}$		Relative positive square speed	$m\ s^{-1}$
	Standard deviation of speed	$km\ h^{-1}$		Relative real square speed	$m\ s^{-1}$
	Speed: 75th - 25th percentile	$km\ h^{-1}$		Relative cubic speed	$m^2\ s^{-2}$
	Maximum speed	$km\ h^{-1}$		Relative positive cubic speed	$m^2\ s^{-2}$
Acceleration-related	Average acceleration	$m\ s^{-2}$		Relative real cubic speed	$m^2\ s^{-2}$
	Average positive acceleration	$m\ s^{-2}$		Root mean square of accel.	$m\ s^{-2}$

Art.Kinema is designed to read an ASCII file containing a speed-time profile, and the program applies an automatic smoothing function to the speed profile if necessary. The time and speed resolution of driving cycles can vary, and some *Art.Kinema* parameters are sensitive to such differences. For example, if a speed profile has a low resolution, too many extreme changes in the calculated acceleration can occur, and the smoothing function is designed to avoid this. Up to three iterations of the smoothing function are applied. This also has the advantage of providing a more consistent basis for comparing different cycles.

2.2.2 Quantitative assessment of driving cycles

Six separate sets of data were defined for use in this part of the work:

(i) *Real-world driving patterns*: This large database contained all driving patterns logged by TRL for vehicles in normal operation on various projects since 1995. The database contained measurements for almost 10,000 trips (more than 73,000 km). Most of the driving patterns were for cars, although data were also collected for LGVs, HGVs and buses. The database is summarised in Table 3. The driving patterns for cars were logged on a variety of routes, ranging from congested urban roads to free-flowing motorways. The HGV measurements were obtained on urban roads, suburban roads and motorways. There is a wide variety of HGVs in use on the road (*e.g*. rigid, articulated, draw-bar), with varying weight and load. However, the only vehicles used by TRL to measure real-world driving patterns were a 17-tonne flat-bed rigid truck and a 38-tonne articulated truck with a curtain-sided trailer, both approximately half-laden. It would be very costly to cover every type of HGV. The data for LGVs and buses were obtained mainly on urban roads, and therefore the majority of trips had a relatively low average speed (maximum 40 $km\ h^{-1}$ for LGVs and 32 $km\ h^{-1}$ for buses).

(ii) *Reference Book driving cycles*: This refers to the 256 driving cycles included in the Reference Book (Section 2.2.1).

(iii) *UKEFD driving cycles*: The driving cycles used to generate the emission factors in the 2002 UK Emission Factor Database. These represent a sub-set of the driving cycles the Reference Book.

(iv) *WSL driving cycles*: The Warren Spring Laboratory cycles, which have been used for testing light-duty vehicles in previous DfT programmes. There are six WSL cycles: ‘congested traffic’, ‘urban’, ‘suburban’, ‘rural’, ‘motorway 90’ and ‘motorway 113’. The WSL cycles represent a sub-set of both the Reference Book driving cycles and the UKEFD driving cycles.

(v) *FiGE driving cycles*: This is the chassis dynamometer simulation of the European legislative test cycle for heavy-duty engines - the European Transient Cycle (ETC) - which has also commonly been used for testing heavy-duty vehicles in DfT research programmes. The cycle has three sub-cycles (‘urban’, ‘suburban’, ‘motorway’). Again, the overall cycle and the three sub-cycles represent a sub-set of both the Reference Book driving cycles and the UKEFD driving cycles.

(vi) *ARTEMIS driving cycles*: This is the set of driving cycles for passenger cars developed within the ARTEMIS project. It consists of various sub-cycles, including ‘urban’, ‘rural’ and ‘motorway’. There are ‘high-speed’ and ‘low-speed’ variants of the motorway cycle.

Table 3: Numbers of real-world trips by research programme and vehicle category.

Programme (Customer)	Years	Location(s)	Road types	Number of trips					Distance (km)	Duration (h)
				Car	LGV	Bus	HGV	Total		
AVERT (DfT)	2002	Southampton	Wide range of urban roads	10	-	-	-	10	187	6
UG106 (DfT)	1996-2001	Gloucester	Wide range of urban roads	1,433	-	-	-	1,433	14,504	459
UG93 (DfT)	1997-1998	Havant	Urban residential with traffic calming	258	-	-	-	258	2,767	80
HOV Lane (HA)	2000	A2/A102 M25-Blackwall	Trunk Road	24	-	-	-	24	1,188	23
M25 VSL (HA)	2000-2001	M25	Motorway	809	-	-	-	809	16,933	271
M42 (HA)	2003-2004	M42 Birmingham	Motorway	346	-	-	203	549	18,987	282
M6 (HA)	2000	M6 Birmingham	Motorway	242	-	-	-	242	3,652	66
OSCAR (EC, DfT)	2003	Central London	City centre	45	-	-	-	45	364	28
UG214 (DfT)	2000-2001	Kingston, Richmond, S’ampton, Havant, Oxford, Gloucester, Reading	Various urban roads with traffic calming	225	367	225	223	1,040	10,219	444
UG127 (DfT)	1997-1999	Bracknell, Harrow, Sand-hurst, Slough, Sutton, Walton-on-Thames.	Urban residential with traffic calming	18	-	-	-	18	106	3
WSL cycles (DfT)	1995	Stevenage, Hitchin, A1(M)	Urban, suburban, rural, motorway	557	-	-	-	557	4,276	88
Total				3,967	367	225	426	4,985	73,183	1,750

The quantitative assessment proceeded in two stages: a ‘coarse’ assessment and a ‘detailed’ assessment. In the coarse assessment the properties of the datasets were compared with the average statistics for vehicle types and road types in Great Britain reported by the Department for Transport (Department for Transport, 2005). In fact, the coarse assessment focussed solely on speed, as other driving cycle parameters are not available on a national basis. In the detailed assessment the characteristics of data sets (ii) to (vi) above - were compared with the characteristics of the real-world driving patterns in data set (i), based upon the *Art.Kinema* parameters.

2.3 Results

2.3.1 Driving cycle Reference Book

A total of 256 driving cycles are presented in the Reference Book (Barlow *et al.*, 2009). As in Table 1, the cycles have been broadly grouped according to the purpose or the measurement programme for which they were developed or used, and the nomenclature for these groups is described in Table 4. The full list of driving cycles included in the Reference Book is given in Table 5. The values for the distance, duration and average speed of each cycle are also provided. Only the period of each cycle which is associated with emission sampling is considered. Where the initial speed or the final speed of a cycle is greater than zero, the 'ramp up' and 'ramp down' sections are not included in the analysis. Descriptions of each driving cycle, including a graph showing speed as a function of time as well as the values of the *Art.Kinema* parameters, are contained in the Reference Book itself (Barlow *et al*., 2009).

Table 4: Nomenclature for the driving cycle groups used in the Reference Book

Driving cycle group	Comments
EU legislative cycles	European test cycles used for type approval purposes – cars, HGVs & buses
US cycles	A variety of cycles from the US, including type approval cycles for cars, HGVs and buses
Japanese legislative cycles	Test cycles used for type approval purposes in Japan – cars
Legislative motorcycle cycles	Harmonised world-wide type approval test cycles for motorcycles
WSL cycles	Car test cycles developed by TRL over the Stevenage and Hitchin routes, used by the former Warren Spring Laboratory for road tests
TRAMAQ UG214 cycles	Test cycles developed within the DfT TRAMAQ programme, project UG214 – cars, LGVs, HGVs & buses
Millbrook cycles	Test cycles developed by Millbrook Proving Ground – HGVs & buses
OSCAR cycles	Test cycles developed within the EC 5^{th} Framework project: OSCAR – cars
ARTEMIS cycles	Test cycles developed within the EC 5^{th} Framework project: ARTEMIS - cars
EMPA cycles	Swiss test cycles developed by EMPA for the UBA
Handbook cycles	The German/Austrian/Swiss (DACH) Handbook of emission factors.
MODEM-IM cycles	Short test cycles developed for inspection & maintenance purposes within the JCS project
INRETS cycles	Test cycles developed by INRETS from data logged in Lyon, France
INRETS short cycles (cold start)	Short versions of the INRETS driving cycles
MODEM cycles	Realistic driving cycle developed in the EC 4^{th} Framework MODEM project, based on data from 60 cars in normal use in six towns in the UK, France and Germany
ARTEMIS WP3141 cycles	Additional test cycles for cars derived within the ARTEMIS project, based on data collected in Naples
Modem-HyZem car cycles	Test cycles developed for evaluating hybrid vehicles
Cycles for business cars	Test cycles developed by INRETS from data collected from cars used for business purposes
Cycles for small LGVs (1.3 to 1.7 t)	Test cycles developed by INRETS for small LGVs
Cycles for 2.5 t LGVs	Test cycles developed by INRETS for medium LGVs
Cycles for 3.5 t LGVs	Test cycles developed by INRETS for large LGVs
MTC cycles	Test cycles developed by MTC for cars
TUG cycles	Test cycle developed by TUG to evaluate the effects of gradient
TRRL cycles	Stylised test cycles developed by TRRL, based on logged data
TRL M25 cycle	High-speed car test cycle developed by TRL, based on data collected on the M25 motorway
BP bus cycle	Bus test cycle developed by BP
TNO bus cycle	Bus test cycle developed by TNO in the Netherlands
FHB motorcycle cycles	Motorcycle test cycles developed by Biel University of applied science, Switzerland

Table 5: Summary of driving cycles in Reference Book.

No	Cycle group	Cycle name	Vehicle category	Distance (m)	Duration (s)	Average speed (km h^{-1})
1	EU legislative cycles	ECE 15	Cars	995	195	18.4
2		Extra Urban Driving Cycle (EUDC)	Cars	6955	400	62.6
3		EUDC, low power vehicles	Cars	6609	400	59.5
4		ECE 15 + EUDC	Cars	11017	1220	32.5
5		New European Driving Cycle (NEDC)	Cars	11017	1180	33.6
6		Braunschweig City Driving Cycle	Buses	10900	1740	22.6
7		FiGE - entire cycle	HGVs	29494	1800	59.0
8		FiGE - part 1	HGVs	3871	600	23.2
9		FiGE - part 2	HGVs	11549	600	69.3
10		FiGE - part 3	HGVs	14075	600	84.5
11	US cycles	FTP-72	Cars	11997	1369	31.6
12		FTP-75	Cars	17783	1874	34.2
13		US06 Supplemental FTP	Cars	12889	596	77.9
14		SC03 Supplemental FTP	Cars	5764	596	34.8
15		EPA New York City Cycle (NYCC)	Cars	1900	598	11.4
16		EPA Highway Fuel Economy Test (HWFET)	Cars	16503	765	77.7
17		IM240	Cars	3153	240	47.3
18		California LA92 Dynamometer Driving Schedule	Cars	15802	1435	39.6
19		UDDS for heavy-duty vehicles	HGVs	8931	1060	30.3
20		Transit Coach Operating Duty Cycle - All	Buses	22634	2830	28.8
21		Transit Coach Operating Duty Cycle - CBD	Buses	3295	560	21.2
22		Transit Coach Operating Duty Cycle - Arterial	Buses	3157	270	42.1
23		Transit Coach Operating Duty Cycle - Commuter	Buses	6433	310	74.7
24		City Suburban Cycle (CSC)	HGVs	10752	1700	22.8
25		New York Composite Cycle	HGVs	4020	1029	14.1
26		New York Bus Cycle	Buses	994	600	6.0
27		Manhattan Bus Cycle	Buses	3333	1089	11.0
28		Orange County Bus (OC Bus) Cycle	Buses	10530	1909	19.9
29		WVU 5-Peak (Truck) Cycle	HGVs	8069	900	32.3
30	Japanese legislative cycles	JP 10 Mode	Cars	663	135	17.7
31		JP 10-15 Mode (3 x 10-mode + 1 x 15-mode)	Cars	4165	660	22.7
32		Japanese New Transient Mode (JE05)	HGVs	13897	1829	27.4
33	Legislative motorcycle cycles	World Motorcycle Test Cycle (WMTC): part 1	Motorcycles	4065	600	24.4
34		World Motorcycle Test Cycle (WMTC): part 2	Motorcycles	9111	600	54.7
35		World Motorcycle Test Cycle (WMTC): part 3	Motorcycles	15736	600	94.4
36		WMTC: part 1, reduced speed	Motorcycles	3935	600	23.6
37		WMTC: part 2, reduced speed	Motorcycles	8969	600	53.8
38		WMTC: part 3, reduced speed	Motorcycles	14436	600	86.6
39	WSL cycles	TRL WSL Urban: large car	Cars	6152	1207	18.4
40		TRL WSL Urban: medium car	Cars	6152	1207	18.4
41		TRL WSL Urban: small car	Cars	6151	1207	18.4
42		TRL WSL Suburban: large car	Cars	5516	481	41.3
43		TRL WSL Suburban: medium car	Cars	5516	481	41.3
44		TRL WSL Suburban: small car	Cars	5516	481	41.3
45		TRL WSL Rural: large car	Cars	10945	589	66.9
46		TRL WSL Rural: medium car	Cars	10949	589	66.9
47		TRL WSL Rural: small car	Cars	10939	588	67.0
48		TRL WSL Motorway 90	Cars	7966	307	93.4
49		TRL WSL Motorway 113	Cars	7972	256	112.1
50		WSL congested traffic cycle	Cars	1921	1029	6.7

Table 5: Summary of driving cycles in Reference Book.(cont.)

No	Cycle group	Cycle name	Vehicle category	Distance (m)	Duration (s)	Average Speed (km h^{-1})
51	TRAMAQ UG214 cycles	UG214 Car01: suburban control	Cars	8258	805	36.9
52		UG214 Car02: traffic calming (road hump)	Cars	6807	804	30.5
53		UG214 Car03: cycle-lane	Cars	7925	1117	25.5
54		UG214 Car04: bus-lane	Cars	7840	1067	26.5
55		UG214 Car05: one-way	Cars	5940	1051	20.3
56		UG214 Car06: mini-roundabout	Cars	6901	808	30.8
57		UG214 Car07: urban traffic control	Cars	7050	914	27.8
58		UG214 Car08: congested control	Cars	3658	1057	12.5
59		UG214 Car09: non-congested control	Cars	9922	950	37.6
60		UG214 Car10: traffic calming (other)	Cars	7993	824	34.9
61		UG214 LGV01: suburban control	LGVs	8816	881	36.0
62		UG214 LGV02: traffic calming (road hump)	LGVs	8028	1027	28.1
63		UG214 LGV03: cycle-lane	LGVs	8870	1195	26.7
64		UG214 LGV04: bus-lane	LGVs	7733	1168	23.8
65		UG214 LGV05: one-way	LGVs	6332	1155	19.7
66		UG214 LGV06: mini-roundabout	LGVs	7299	842	31.2
67		UG214 LGV07: urban traffic control	LGVs	6733	1006	24.1
68		UG214 LGV08: congested control	LGVs	3268	1142	10.3
69		UG214 LGV09: non-congested control	LGVs	10649	1016	37.7
70		UG214 LGV10: traffic calming (other)	LGVs	8492	909	33.6
71		UG214 HGV01: suburban control	HGVs	5122	790	23.3
72		UG214 HGV02: traffic calming (road hump)	HGVs	5756	1010	20.5
73		UG214 HGV03: cycle-lane	HGVs	6828	985	25.0
74		UG214 HGV04: bus-lane	HGVs	6560	930	25.4
75		UG214 HGV05: one-way	HGVs	4019	947	15.3
76		UG214 HGV06: mini-roundabouts	HGVs	5802	927	22.5
77		UG214 HGV07: urban traffic control	HGVs	5069	954	19.1
78		UG214 HGV08: congested control	HGVs	2514	835	10.8
79		UG214 HGV09: non-congested control	HGVs	8810	875	36.3
80		UG214 HGV10: traffic calming (other)	HGVs	6706	895	27.0
81		UG214 Bus01: traffic calming (road hump)	Buses	5318	944	20.3
82		UG214 Bus02: traffic calming (other)	Buses	5938	855	25.0
83		UG214 Bus03: cycle-lane	Buses	5652	1080	18.8
84		UG214 Bus04: bus-lane	Buses	8345	1192	25.2
85		UG214 Bus05: one-way	Buses	4360	941	16.7
86		UG214 Bus06: mini-roundabout	Buses	7880	1076	26.4
87		UG214 Bus07: urban traffic control	Buses	5413	894	21.8
88		UG214 Bus08: congested control	Buses	3079	1051	10.6
89		UG214 Bus09: non-congested control	Buses	7610	983	27.9
90		UG214 Bus10: suburban control	Buses	6395	886	26.0
91	Millbrook cycles	Millbrook Heavy Duty: urban	HGVs	4059	814	18.0
92		Millbrook Heavy Duty: suburban	HGVs	11098	889	44.9
93		Millbrook Heavy Duty: motorway	HGVs	17649	780	81.5
94		Millbrook Westminster Dust Cart: Depot	HGVs	5252	780	24.2
95		Millbrook Westminster Dust Cart: Commercial	HGVs	1464	780	6.8
96		Millbrook Westminster Dust Cart: domestic	HGVs	124	780	0.6
97		Millbrook W'minster London Bus: outer London	Buses	6474	1380	16.9
98		Millbrook W'minster London Bus: inner London	Buses	2509	901	10.0

Table 5: Summary of driving cycles in Reference Book.(cont.)

No	Cycle group	Cycle name	Vehicle category	Distance (m)	Duration (s)	Average speed (km h^{-1})
99	OSCAR cycles	OSCAR C	Cars	3979	401	35.7
100		OSCAR D1	Cars	2696	429	22.6
101		OSCAR D2	Cars	2328	363	23.1
102		OSCAR E	Cars	2055	371	19.9
103		OSCAR F	Cars	1601	423	13.6
104		OSCAR G1	Cars	1556	455	12.3
105		OSCAR G2	Cars	1121	350	11.5
106		OSCAR H1	Cars	801	370	7.8
107		OSCAR H2	Cars	952	424	8.1
108		OSCAR H3	Cars	855	374	8.2
109	ARTEMIS cycles	Artemis urban_incl_start	Cars	4874	993	17.7
110		Artemis rural_incl_pre_post	Cars	17275	1082	57.5
111		Artemis mw_150_incl_pre_post	Cars	29547	1068	99.6
112		Artemis mw_130_incl_pre_post	Cars	28737	1068	96.9
113		Artemis URM150	Cars	51695	3143	59.2
114		Artemis URM130	Cars	50886	3143	58.3
115		Artemis HighMot_urban_total	Cars	5438	998	19.6
116		Artemis HighMot_urbdense_total	Cars	3084	787	14.1
117		Artemis HighMot_freeurban_total	Cars	5378	822	23.6
118		Artemis HighMot_rural_total	Cars	16613	1043	57.3
119		Artemis HighMot_motorway_total	Cars	30209	1065	102.1
120		Artemis LowMot_urban_total	Cars	5319	1028	18.6
121		Artemis LowMot_urbdense_total	Cars	3068	761	14.5
122		Artemis LowMot_freeurban_total	Cars	5377	808	24.0
123		Artemis LowMot_rural_total	Cars	15439	1036	53.7
124		Artemis LowMot_motorway_total	Cars	28885	1064	97.7
125	EMPA cycles	EMPA B	Cars	27525	2024	49.0
126		EMPA L2	Cars	44622	2290	70.2
127		EMPA BAB	Cars	32637	1000	117.5
128		EMPA Beschl	Cars	5379	963	20.1
129		EMPA C-1	Cars	1198	1348	3.2
130		EMPA C-2	Cars	17304	828	75.2
131		EMPA C-3	Cars	27377	855	115.3
132		EMPA C-4	Cars	9403	1094	30.9
133		EMPA C-5	Cars	18184	983	66.6
134		EMPA C-6	Cars	29866	1040	103.4
135		EMPA EL1	Cars	34682	1228	101.7
136		EMPA EL2	Cars	15256	1731	31.7
137		EMPA K1	Cars	53218	2190	87.5
138		EMPA K2	Cars	19702	2045	34.7
139		EMPA Kreisel	Cars	4878	513	34.2
140		EMPA LSA	Cars	6068	770	28.4
141		EMPA Pendel	Cars	14068	924	54.8
142		EMPA RX	Cars	12394	1169	38.2
143		EMPA T85	Cars	9416	399	85.0
144		EMPA T100	Cars	11086	399	100.0
145		EMPA T115	Cars	12748	399	115.0
146		EMPA T130	Cars	14408	399	130.0

Table 5: Summary of driving cycles in Reference Book.(cont.)

No	Cycle group	Cycle name	Vehicle category	Distance (m)	Duration (s)	Average speed (km h^{-1})
147	Handbook cycles	Handbook R1 incl pre	Cars	45075	1500	108.2
148		Handbook R2 incl pre	Cars	25054	1222	73.8
149		Handbook R3 incl pre	Cars	15911	1208	47.4
150		Handbook R4 incl pre	Cars	6970	1456	17.2
151		Handbook S1 incl pre	Cars	76934	2581	107.3
152		Handbook S2 incl pre	Cars	55271	2572	77.4
153		Handbook S3 incl pre	Cars	31341	2537	44.5
154		Handbook S4 incl pre	Cars	10831	2534	15.4
155		Handbook_DrivingPatterns	Cars	83493	4820	62.4
156	MODEM-IM cycles	modemIM Urban_Slow	Cars	1709	428	14.4
157		modemIM Urban_Free_Flow	Cars	2251	355	22.8
158		modemIM Road	Cars	8490	712	42.9
159		modemIM Motorway	Cars	12683	452	101.0
160		TÜV-A	Cars	1970	200	35.5
161		modemIM short	Cars	2248	255	31.7
162		EMPA M1	Cars	10199	1140	32.2
163		EMPA M2	Cars	14934	807	66.6
164	INRETS cycles	INRETS urbainlent1	Cars	844	805	3.8
165		INRETS urbainlent2	Cars	1672	814	7.4
166		INRETS urbainfluide1	Cars	1885	680	10.0
167		INRETS urbainfluide2	Cars	5624	1054	19.2
168		INRETS urbainfluide3	Cars	7239	1067	24.4
169		INRETS route1	Cars	7815	888	31.7
170		INRETS route2	Cars	9278	809	41.3
171		INRETS route3	Cars	15695	996	56.7
172		INRETS autoroute1	Cars	15126	734	74.2
173		INRETS autoroute2	Cars	26489	1009	94.5
174	INRETS short cycles (cold start)	INRETS urbainlentcourt	Cars	421	208	7.3
175		INRETS urbainfluidecourt	Cars	1002	189	19.1
176		INRETS routecourt (old version)	Cars	1438	126	41.1
177		INRETS routecourt	Cars	1438	126	41.1
178	MODEM cycles	MODEM urban1	Cars	3449	635	19.6
179		MODEM urban2	Cars	877	168	18.8
180		MODEM urban3	Cars	1086	282	13.9
181		MODEM urban4	Cars	407	132	11.1
182		MODEM urban5	Cars	6336	1027	22.2
183		MODEM urban6	Cars	129	91	5.1
184		MODEM urban7	Cars	840	100	30.2
185		MODEM urban8	Cars	1106	250	15.9
186		MODEM urban9	Cars	201	95	7.6
187		MODEM urban10	Cars	1868	430	15.6
188		MODEM urban11	Cars	11346	962	42.5
189		MODEM urban12	Cars	2445	423	20.8
190		MODEM urban13	Cars	2620	526	17.9
191		MODEM urban14	Cars	3415	383	32.1
192		MODEM MODEM_1	Cars	5819	1217	17.2
193		MODEM MODEM_2	Cars	7305	1218	21.6
194		MODEM MODEM_3	Cars	3175	775	14.8
195		MODEM MODEM_6	Cars	6036	909	23.9
196		MODEM EVAP	Cars	2361	553	15.4

Table 5: Summary of driving cycles in Reference Book.(cont.)

No	Cycle group	Cycle name	Vehicle category	Distance (m)	Duration (s)	Average speed (km h^{-1})
197	ARTEMIS WP3141 cycles	MODEM urban5713	Cars	9082	1426	22.9
198		Napoli 6_17	Cars	16469	1038	57.1
199		Napoli 15_18_21	Cars	4473	1070	15.1
200		Napoli 10_23	Cars	3362	1081	11.2
201		Naples Driving Patterns	Cars	87270	11061	28.4
202	Modem-HyZem car cycles	MODEM HyZem urban	Cars	3473	560	22.3
203		MODEM HyZem road_total	Cars	11230	843	48.0
204		MODEM HyZem motorway_total	Cars	46210	1804	92.2
205		MODEM HyZem urban1	Cars	4188	720	20.9
206		MODEM HyZem urban3	Cars	2917	583	18.0
207		MODEM HyZem road1_total	Cars	7827	700	40.3
208		MODEM HyZem road2_total	Cars	27331	1494	65.9
209		MODEM HyZem motorway1_total	Cars	42703	1868	82.3
210	Cycles for business cars	LDV_PVU commercial cars urban_1	Cars	3325	583	20.5
211		LDV_PVU commercial cars urban_2	Cars	3730	476	28.2
212		LDV_PVU commercial cars urban_3	Cars	2477	502	17.8
213		LDV_PVU commercial cars road_total	Cars	14086	917	55.3
214		LDV_PVU commercial cars motorway_1_total	Cars	19657	1012	69.9
215		LDV_PVU commercial cars motorway_2_total	Cars	26967	1082	89.7
216	Cycles for small LGVs (1.3 to 1.7 t)	LDV_PVU light vans-Empty urban1	LGVs	2302	680	12.2
217		LDV_PVU light vans-Loaded urban1	LGVs	3237	832	14.0
218		LDV_PVU light vans-Empty urban2	LGVs	2923	526	20.0
219		LDV_PVU light vans-Loaded urban2	LGVs	2918	516	20.4
220		LDV_PVU light vans-Empty road	LGVs	5019	483	37.4
221		LDV_PVU light vans-Loaded road	LGVs	5815	482	43.4
222		LDV_PVU light vans-Empty motorway_total	LGVs	18059	802	81.1
223		LDV_PVU light vans-Loaded motorway_total	LGVs	17669	832	76.5
224	Cycles for 2.5 t LGVs	LDV_PVU 2.5t vans-Empty urban1	LGVs	2586	546	17.1
225		LDV_PVU 2.5t vans-Loaded urban1	LGVs	2584	548	17.0
226		LDV_PVU 2.5t vans-Empty urban2	LGVs	4753	640	26.7
227		LDV_PVU 2.5t vans-Loaded urban2	LGVs	5737	817	25.3
228		LDV_PVU 2.5t vans delivery	LGVs	2424	633	13.8
229		LDV_PVU 2.5t vans-Empty rural_total	LGVs	9964	774	46.3
230		LDV_PVU 2.5t vans-Loaded rural_total	LGVs	10525	652	58.1
231		LDV_PVU 2.5t vans-Empty motorway_total	LGVs	22653	904	90.2
232		LDV_PVU 2.5t vans-Loaded motorway_total	LGVs	27524	1198	82.7
233	Cycles for 3.5 t LGVs	LDV_PVU 3.5t vans slow_urban	LGVs	2194	649	12.2
234		LDV_PVU 3.5t vans free-flow_urban	LGVs	2894	467	22.3
235		LDV_PVU 3.5t vans delivery	LGVs	1594	546	10.5
236		LDV_PVU 3.5t vans rural_total	LGVs	11474	819	50.4
237		LDV_PVU 3.5t vans motorway_total	LGVs	31330	1280	88.1
238	MTC cycles	MTC Essing_congested	Cars	1426	1049	4.9
239		MTC Essing_freeflow	Cars	9609	506	68.4
240	TUG cycles	TUG Ries_RoadGradient	Cars	6840	510	48.3
241	TRRL cycles	TRRL 1.1	Cars	4464	580	27.7
242		TRRL 1.2	Cars	11659	551	76.2
243		TRRL 1.3	Cars	12017	566	76.4
244		TRRL 1.4	Cars	6211	573	39.0
245		TRRL 2.1	Cars	6211	573	39.0
246		TRRL 2.2	Cars	13744	532	93.0
247		TRRL 2.3	Cars	13050	501	93.8
248		TRRL 2.4	Cars	4595	592	27.9

Table 5: Summary of driving cycles in Reference Book.(cont.)

No	Cycle group	Cycle name	Vehicle category	Distance (m)	Duration (s)	Average speed (km h^{-1})
249	TRL M25 cycle	M25 High speed cycle	Cars	98579	3500	101.4
250	BP bus cycle	BP Bus cycle	Buses	5556	903	22.2
251	TNO bus cycle	TNO Bus cycle	Buses	5248	898	21.0
252	FHB motorcycle cycles	FHB Motorcycle cycle - All	Motorcycles	27427	1868	52.9
253		FHB Motorcycle cycle - Zentrum	Motorcycles	2464	401	22.1
254		FHB Motorcycle cycle - Peripherie	Motorcycles	3835	466	29.6
255		FHB Motorcycle cycle - Ueberland	Motorcycles	7311	524	50.2
256		FHB Motorcycle cycle - Autobahn	Motorcycles	13814	477	104.3

The average speeds of the cycles included in each dataset are shown in Figure 4. The real-world UK driving patterns, with all vehicle types included, had a wide range of average speed, from just above zero to around 118 km h^{-1}. However, the upper limit was restricted as the drivers were instructed to obey speed limits. The cycles in the Reference Book (again, all vehicle types) covered a similar range of average speeds, from 0.5 km h^{-1} (Millbrook Westminster Dust Cart: domestic cycle) to 117 km h^{-1} (EMPA BAB cycle), but also included the high-speed EMPA T130 cycle with an average speed of 130 km h^{-1}. The UKEFD cycles had the same range of average speeds as the Reference Book cycles, but had less coverage at certain speeds. The FiGE cycles had average speeds of between 23 km h^{-1} and 84 km h^{-1}. The higher speed is close to the limited maximum speed of 90 km h^{-1} for modern heavy-duty vehicles (see Section 2.3.2). The WSL driving cycles ranged between 6 km h^{-1} and 112 km h^{-1}, with the cycles being spread fairly evenly across the speed range. The ARTEMIS driving cycle consists of sub-cycles with average speeds ranging from 14 km h^{-1} ('urbdense' – congested urban sub-cycle) to 102 km h^{-1} (150 km h^{-1} motorway sub-cycle). However, the average speeds of the sub-cycles are clustered around 20, 60 and 100 km h^{-1}.

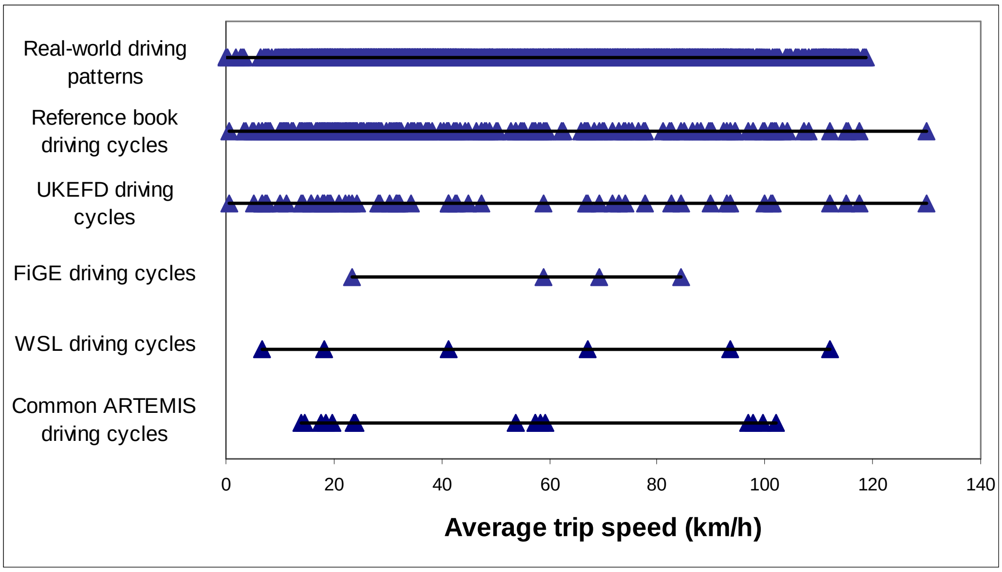

Figure 4: Average speeds of the various driving cycles. Each blue triangle represents a single driving pattern or driving cycle (including sub-cycles).

2.3.2 Coarse assessment of driving cycles

In the coarse assessment, the properties of the five datasets described in Section 2.2.2 were compared with national statistics on vehicle operation. The assessment focussed solely on speed, as other driving cycle parameters were not available on a national basis. The Transport Statistics Division of DfT publishes average speed distributions measured on roads in Great Britain (Department for Transport, 2005). These are summarised for urban roads in Table 6 and for non-urban roads in Table 7. The speed distributions for the various vehicle types are also plotted in Appendix D of this Report. It is assumed that these statistics broadly reflect UK conditions.

From the information given in Table 6 it can be seen that most vehicles on urban roads in Great Britain are travelling at speeds which are between 20 mph (64 km h^{-1}) and 50 mph (80 km h^{-1}), and only a small proportion of vehicles are travelling at speeds below 20 mph. This implies that for inventory purposes the accurate characterisation of emissions at very low speeds is likely to be less important than accurate characterisation at higher speeds. However, it is important to note that accurate emission factors at low speeds remain important for air quality assessments, especially those assessments which relate to traffic congestion in some way. Indeed, several of the driving cycles used to derive the UK emission factors do have an average speed of less than 32 km h^{-1}.

Table 6: Percentages of vehicles having speeds in excess of a stated speed on urban roads In Great Britain (adapted from Department of Transport *et al.*, 2005).

Road type	Vehicle type	% of vehicles exceeding a given speed (mph, km h^{-1} in brackets)							
		>20 (32)	>30 (48)	>40 (64)	>50 (80)	>60 (97)	>70 (113)	>80 (129)	>90 (145)
Urban roads: roads with a 40 mph speed limit	Motorcycles	95%	81%	37%	9%	2%	-	-	-
	Cars	97%	85%	27%	3%	-	-	-	-
	LGVs	96%	84%	29%	4%	1%	-	-	-
	Buses/coaches	97%	81%	13%	-	-	-	-	-
	2-axle rigid HGVs	95%	81%	22%	2%	-	-	-	-
	3-axle rigid HGVs	97%	83%	20%	1%	-	-	-	-
	4-axle rigid HGVs	98%	88%	26%	1%	-	-	-	-
	4-axle articulated HGVs	98%	87%	26%	2%	-	-	-	-
	5+-axle articulated HGVs	98%	88%	25%	1%	-	-	-	-
Urban roads: roads with a 30 mph speed limit	Motorcycles	87%	48%	11%	2%	-	-	-	-
	Cars	94%	53%	6%	-	-	-	-	-
	LGVs	92%	53%	6%	-	-	-	-	-
	Buses/coaches	91%	28%	1%	-	-	-	-	-
	2-axle rigid HGVs	91%	48%	5%	-	-	-	-	-
	3-axle rigid HGVs	93%	46%	1%	-	-	-	-	-
	4-axle rigid HGVs	96%	54%	2%	-	-	-	-	-
	4-axle articulated HGVs	925	46%	2%	-	-	-	-	-
	5+-axle articulated HGVs	97%	54%	2%	-	-	-	-	-

The values in Table 7 indicate that around half of the cars on motorways (56%) and dual-carriageways (48%) are travelling at speeds for which emissions have not previously been routinely measured. One area of concern is therefore extent to which the driving cycles currently used for emission measurement cover the higher speeds encountered in the UK.

The majority of heavy-duty vehicles over 7.5 t GVW have been fitted with speed limiters since the early 1990s. A limiter restricts the maximum speed to 56 mph (90 km h^{-1}) for goods vehicles and 62 mph (100 km h^{-1}) for buses. Prior to 1 January 2005 there was no requirement for goods vehicles under 7.5 t (or buses with more than 8 passenger seats) to be fitted with a speed limiter[8]. Vehicles registered between 1 October 2001 and 31 December 2004 (inclusive), will also need to be fitted with a speed limiter. This is reflected in the speed distributions - although the vast majority of large goods vehicles (rigid HGVs with 3 axles or more and articulated HGVs) have speeds of less than 60 mph (97 km h^{-1}), 2-axle rigid HGVs have higher speeds.

[8] http://www.vosa.gov.uk/vosacorp/repository/Speed%20Limiters%20-%20New%20Regulations.pdf

The highest speed sub-cycle of the FiGE cycle, which is normally used to test HGVs, has an average speed of 84 km h^{-1}. The FiGE cycle is therefore suitable for testing speed-limited HGVs and buses, but it does not cover the highest speeds which could be reached with an unrestricted vehicle (pre-October 2001). In addition, the slowest FiGE sub-cycle has an average speed of 23 km h^{-1}. To determine emissions from such vehicles under congested traffic conditions, a much slower driving cycle would be required.

Table 7: Percentages of vehicles having speeds in excess of a stated speed for non-urban roads In Great Britain (adapted from Department for Transport *et al.*, 2005).

Road type	Vehicle type	% of vehicles exceeding a given speed (mph, km h^{-1} in brackets)							
		>20 (32)	>30 (48)	>40 (64)	>50 (80)	>60 (97)	>70 (113)	>80 (129)	>90 (145)
Non-urban roads: motorways	Motorcycles	-	-	-	96%	80%	59%	28%	8%
	Cars	-	-	-	97%	85%	56%	19%	3%
	LGVs	-	-	-	96%	81%	51%	17%	3%
	Buses/coaches	-	-	-	94%	50%	2%	-	-
	2-axle rigid HGVs	-	-	-	94%	47%	18%	4%	1%
	3-axle rigid HGVs	-	-	-	88%	6%	-	-	-
	4-axle rigid HGVs	-	-	-	87%	1%	-	-	-
	4-axle articulated HGVs	-	-	-	92%	2%	-	-	-
	5+-axle articulated HGVs	-	-	-	92%	1%	-	-	-
Non-urban roads: dual carriageways	Motorcycles	-	100%	98%	87%	69%	48%	21%	-
	Cars	-	100%	100%	97%	82%	48%	14%	-
	LGVs	-	100%	100%	96%	77%	44%	13%	-
	Buses/coaches	-	100%	99%	89%	40%	3%	1%	-
	2-axle rigid HGVs	-	100%	99%	89%	40%	14%	3%	-
	3-axle rigid HGVs	-	100%	99%	78%	7%	3%	1%	-
	4-axle rigid HGVs	-	100%	99%	78%	1%	-	-	-
	4-axle articulated HGVs	-	99%	98%	80%	3%	-	-	-
	5+-axle articulated HGVs	-	99%	99%	87%	1%	-	-	-
Non-urban roads: single carriageways	Motorcycles	99%	93%	80%	52%	25%	10%	-	-
	Cars	100%	98%	83%	41%	10%	2%	-	-
	LGVs	100%	97%	81%	40%	11%	2%	-	-
	Buses/coaches	99%	96%	73%	24%	2%	-	-	-
	2-axle rigid HGVs	99%	96%	77%	30%	5%	1%	-	-
	3-axle rigid HGVs	99%	93%	69%	18%	-	-	-	-
	4-axle rigid HGVs	99%	90%	62%	17%	-	-	-	-
	4-axle articulated HGVs	98%	92%	72%	21%	-	-	-	-
	5+-axle articulated HGVs	100%	98%	80%	30%	1%	-	-	-

2.3.3 Detailed assessment of driving cycles

In the detailed assessment, all the driving cycles and real-world driving patterns were analysed using the *Art.Kinema* program. A large number of parameters were generated for each driving cycle or pattern. The correlation of between each parameter and every other parameter was calculated for the entire data set. The resulting correlation matrix is given in Table 8. The value of the correlation coefficient (r) ranges from -1.0 to +1.0. A perfect positive correlation is indicated by +1.0, and a perfect negative correlation by -1.0. A cut off point of plus or minus 0.71 was used to identify the strongest correlations (this being equivalent to an r^2 value of 0.5). The values indicating a strong positive or negative correlation are shown in normal font, with all other values being shown in a light font (along with the unity values associated with comparisons between identical parameters).

Table 8: Correlation matrix (*r* values) of the *Art.Kinema* parameters: all data (n = 4985)

n	4985	%cruise	%acc	%dec	%brake	%stop	v_avrg_trip	v_avrg_drive	v_stdv	v_IQR	v_max	a_avrg	a_pos_avrg	a_neg_avrg	a_stdv	a_pos_stdv	a_neg_stdv	a_IQR	acc_rate	stop_rate	stop_T_avrg	stop_dist	RPA	PKE	CSPKE	RPS	RRS	RSS	RPSS	RRSS	RCS	RPCS	RRCS	RMSA
% of cruising	%cruise	1.00																																
% of time accelerating	%acc	-0.70	1.00																															
% of time decelerating	%dec	-0.71	0.79	1.00																														
% of time braking	%brake	-0.83	0.70	0.71	1.00																													
% of time standing	%stop	-0.56	-0.15	-0.12	0.31	1.00																												
average speed (trip)	v_avrg_trip	0.64	-0.26	-0.26	-0.55	-0.60	1.00																											
average driving speed	v_avrg_drive	0.59	-0.27	-0.28	-0.51	-0.50	0.99	1.00																										
standard dev. of speed	v_stdv	-0.11	0.10	0.09	0.28	0.05	0.25	0.32	1.00																									
75th - 25th percentile	v_IQR	-0.37	0.18	0.16	0.42	0.32	-0.02	0.08	0.84	1.00																								
maximum speed	v_max	0.17	-0.04	-0.04	-0.05	-0.20	0.69	0.74	0.76	0.54	1.00																							
average acceleration	a_avrg	-0.09	0.11	0.00	0.02	0.06	-0.10	-0.10	-0.06	-0.03	-0.09	1.00																						
average pos. acc.	a_pos_avrg	-0.66	0.45	0.41	0.77	0.41	-0.26	-0.18	0.42	0.57	0.26	0.00	1.00																					
average neg. acc.	a_neg_avrg	0.62	-0.50	-0.34	-0.73	-0.36	0.22	0.14	-0.42	-0.57	-0.27	0.05	-0.97	1.00																				
standard dev. of acc.	a_stdv	-0.64	0.48	0.39	0.75	0.38	-0.21	-0.13	0.53	0.64	0.33	-0.03	0.96	-0.96	1.00																			
standard dev. of positive acc.	a_pos_stdv	-0.53	0.34	0.35	0.67	0.33	-0.13	-0.05	0.63	0.65	0.40	-0.01	0.88	-0.84	0.94	1.00																		
standard dev. of negative acc.	a_neg_stdv	-0.47	0.42	0.24	0.60	0.25	-0.06	0.02	0.61	0.63	0.43	-0.08	0.86	-0.90	0.95	0.91	1.00																	
75th - 25th percentile	a_IQR	-0.70	0.74	0.67	0.86	0.12	-0.28	-0.25	0.27	0.40	0.13	0.03	0.82	-0.82	0.79	0.65	0.67	1.00																
nr. of acc. per km	acc_rate	-0.08	-0.07	-0.06	0.00	0.21	-0.15	-0.15	-0.12	-0.08	-0.17	0.00	0.00	0.01	-0.03	-0.04	-0.06	-0.02	1.00															
stops per km	stop_rate	-0.04	-0.08	-0.08	-0.03	0.16	-0.04	-0.04	-0.03	-0.02	-0.05	0.00	-0.01	0.01	-0.02	-0.02	-0.02	-0.03	0.98	1.00														
average stop duration	stop_T_avrg	-0.34	0.15	0.13	0.43	0.32	-0.45	-0.41	0.34	0.32	-0.10	0.01	0.26	-0.25	0.34	0.39	0.33	0.22	0.02	0.01	1.00													
average distance between stops	stop_dist	-0.23	0.10	0.07	0.35	0.23	-0.33	-0.31	0.35	0.28	-0.05	-0.01	0.19	-0.18	0.28	0.34	0.29	0.15	0.00	0.01	0.98	1.00												
Relative Positive Acceleration	RPA	-0.76	0.53	0.46	0.83	0.47	-0.39	-0.32	0.36	0.53	0.18	0.03	0.96	-0.94	0.94	0.83	0.82	0.85	0.02	0.00	0.30	0.22	1.00											
Positive Kinetic Energy	PKE	-0.75	0.53	0.44	0.82	0.47	-0.37	-0.29	0.41	0.56	0.22	0.04	0.95	-0.94	0.95	0.84	0.84	0.84	-0.02	-0.02	0.32	0.24	0.99	1.00										
Cumulative Squared PKE	CSPKE	-0.33	0.24	0.19	0.49	0.20	0.12	0.20	0.60	0.64	0.60	-0.08	0.84	-0.85	0.85	0.81	0.83	0.65	-0.04	-0.01	0.12	0.09	0.79	0.79	1.00									
Relative Positive Speed	RPS	-0.65	0.57	0.41	0.61	0.31	-0.49	-0.46	0.25	0.31	-0.08	0.11	0.27	-0.31	0.41	0.35	0.34	0.43	-0.01	-0.02	0.46	0.39	0.46	0.50	0.13	1.00								
Relative Real Speed	RRS	0.86	-0.55	-0.57	-0.94	-0.55	0.61	0.55	-0.21	-0.41	0.07	-0.03	-0.81	0.76	-0.77	-0.67	-0.60	-0.79	-0.07	-0.02	-0.40	-0.29	-0.89	-0.87	-0.53	-0.57	1.00							
Relative Square Speed	RSS	0.48	-0.23	-0.22	-0.39	-0.41	0.93	0.96	0.54	0.30	0.88	-0.11	-0.04	0.01	0.02	0.11	0.16	-0.15	-0.17	-0.05	-0.31	-0.22	-0.17	-0.14	0.36	-0.36	0.42	1.00						
Relative Positive Square Speed	RPSS	0.18	0.03	-0.02	-0.09	-0.28	0.73	0.78	0.73	0.49	0.89	-0.07	0.10	-0.14	0.24	0.31	0.35	0.06	-0.17	-0.05	-0.07	-0.01	0.05	0.10	0.45	0.11	0.16	0.88	1.00					
Relative Real Square Speed	RRSS	0.65	-0.36	-0.35	-0.61	-0.50	0.96	0.97	0.37	0.10	0.74	-0.10	-0.30	0.26	-0.24	-0.13	-0.08	-0.38	-0.16	-0.04	-0.39	-0.28	-0.42	-0.39	0.10	-0.47	0.65	0.96	0.77	1.00				
Relative Cubic Speed	RCS	0.40	-0.22	-0.20	-0.30	-0.32	0.87	0.92	0.57	0.35	0.88	-0.12	0.07	-0.10	0.12	0.19	0.23	-0.07	-0.13	-0.03	-0.29	-0.21	-0.06	-0.04	0.46	-0.33	0.31	0.97	0.87	0.90	1.00			
Relative Positive Cubic Speed	RPCS	0.23	-0.07	-0.08	-0.13	-0.25	0.77	0.82	0.70	0.48	0.91	-0.10	0.16	-0.19	0.25	0.33	0.36	0.06	-0.13	-0.03	-0.14	-0.08	0.08	0.10	0.54	-0.06	0.16	0.92	0.96	0.80	0.95	1.00		
Relative Real Cubic Speed	RRCS	0.55	-0.32	-0.29	-0.49	-0.41	0.94	0.96	0.44	0.20	0.80	-0.12	-0.14	0.12	-0.10	-0.01	0.04	-0.26	-0.13	-0.03	-0.37	-0.28	-0.27	-0.25	0.26	-0.43	0.51	0.98	0.82	0.97	0.97	0.89	1.00	
Root Mean Square of Acceleration	RMSA	-0.82	0.46	0.41	0.80	0.63	-0.67	-0.61	0.15	0.37	-0.17	0.03	0.83	-0.80	0.82	0.73	0.69	0.70	0.18	0.12	0.41	0.31	0.90	0.88	0.52	0.51	-0.89	-0.49	-0.27	-0.69	-0.39	-0.25	-0.56	1.00

It should be noted that there are natural relationships between some the parameters which do not differ for different cycles. For example, the average driving speed is generally going to be closely related to the average trip speed. Indeed, most of the speed-related parameters have strong correlations with the other speed-related parameters, although there are a few exceptions (*e.g.* relative positive speed and relative real speed do not show a good correlation, although the latter has a strong correlation with some of the acceleration parameters). Similarly, there are good correlations between the various acceleration-related parameters, including positive kinetic energy.

For each of the datasets listed in Section 2.2.2, each *Art.Kinema* parameter and each vehicle category (cars, LGVs, HGVs and buses) a frequency distribution was obtained. As average speed is commonly used to describe driving cycles, each of the *Art.Kinema* parameters was plotted against the average trip speed. A few selected examples are discussed below for each vehicle category. The average *Art.Kinema* parameters for each dataset and each vehicle category are listed in Appendix E.

Cars

Figure 5 shows the average speed distributions for cars. In the legend, the heading 'Driving cycles' refers to the Reference Book. The *x*-axis indicates the maximum value of each distribution bin (*e.g.* '20' contains the speeds between 10 and 20 km h^{-1}).The *y*-axis simply defines the relative frequency of driving patterns in each database. Each distribution of real-world driving patterns is dependent upon the nature of the measurement programmes included in the database, and its shape cannot therefore be said to be truly representative of the UK average speed distribution (either in terms of vehicles or vehicle-kilometres driven). However, the range of speeds is important, as this range must be covered by the emission factors. In fact, the real-world driving patterns, the Reference Book driving cycles and the UKEFD cycles have broadly similar average speed distributions, with a peak at lower speeds. As there are only six WSL cycles, the distribution is very simple, with each cycle falling in a separate bin. However, the WSL cycles do cover much of the speed range observed in the real-world driving patterns, with only speeds higher than 120 km h^{-1} not being represented. The ARTEMIS sub-cycles appear to cover most of the range of vehicle speeds in the UK, the exception being the highest speeds of the real-world driving patterns.

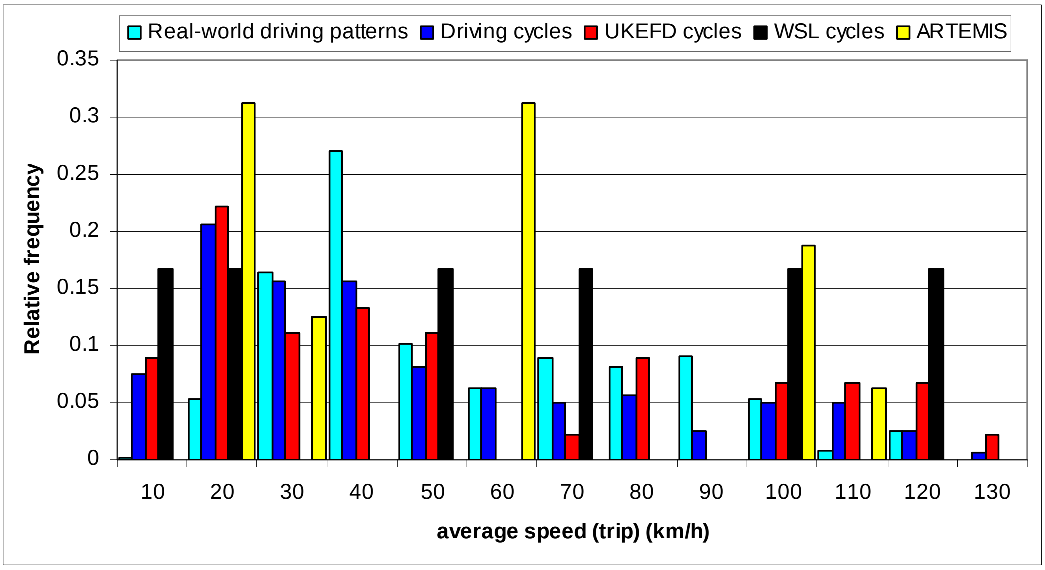

Figure 5: Distributions of average trip speed – cars.

The standard deviation is one measure of the amount of speed variation in a cycle. The distributions of the standard deviation of speed are shown in Figure 6. The distributions for the different data sets were similar, although the WSL cycles may contain less variation in speed compared with real-world driving. The ARTEMIS cycle has a greater proportion of high standard deviations in its sub-cycles than the other cycles.

The standard deviation of the speed within each cycle is shown plotted against average speed in Figure 7. Linear trend lines have been plotted though the data points to highlight similarities and differences between the different data sets. However, the data appear to form a parabola (an inverted 'U'). At very low average cycle speeds the instantaneous speeds also tends to be low, and hence the standard deviation tends to be low. At very high average speeds the instantaneous speeds tend to be high, and again the variation in speed is small. However, cycles with a medium average speed could have a large range of speeds, and hence a large standard deviation. The linear trends lines indicate that the real-world driving patterns and the Reference Book driving cycles have a similar magnitude in their standard deviation, although the slopes differ slightly. The UKEFD cycles have a lower standard deviation, while that of the WSL cycles is much lower than those of the others. The ARTEMIS sub-cycles appear to have relatively high standard deviations at high speeds compared with the other data sets.

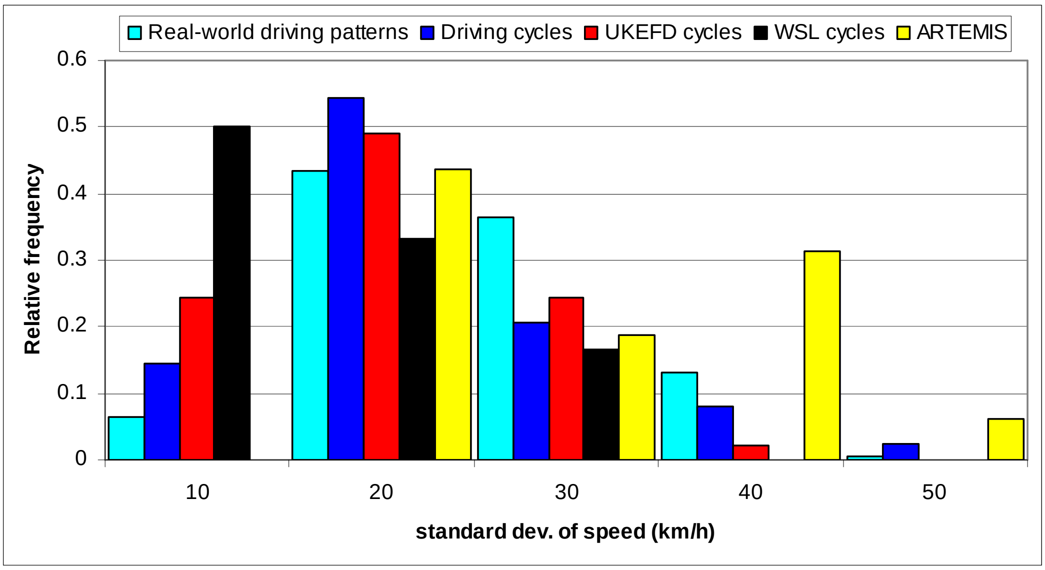

Figure 6: Distributions of standard deviation of speed – cars.

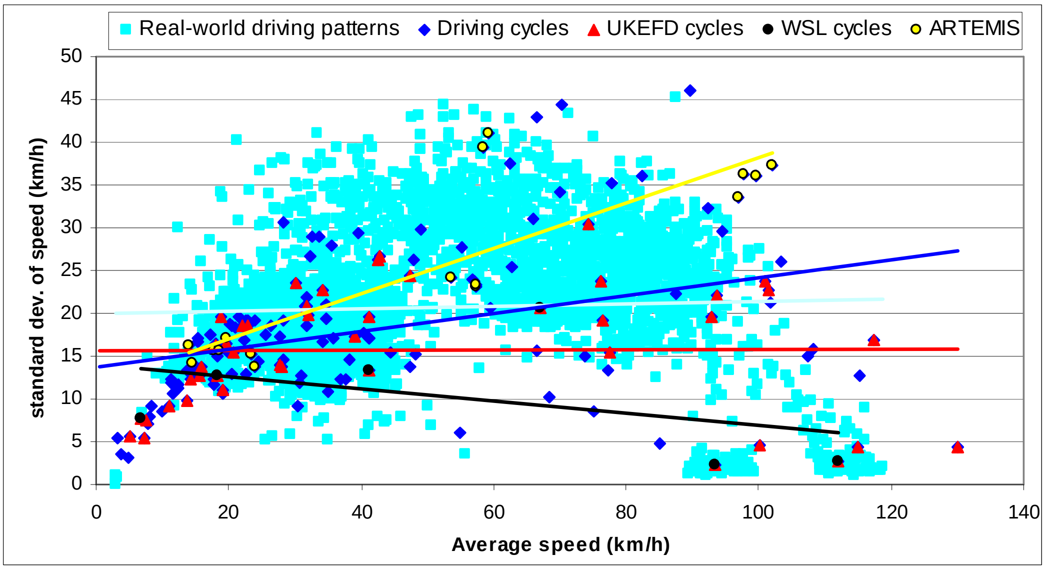

Figure 7: Standard deviation of speed plotted against average speed – cars.

Figure 8 shows the average positive acceleration of each cycle and trip plotted against the average speed. Again, linear models have been fitted to the different data sets. The regression lines for the real-world driving patterns, Reference Book driving cycles and UKEFD cycles are very similar. Although the regression line for the WSL cycles and ARTEMIS cycles have a similar gradient to the regression lines for the other data sets, the

WSL cycles trend-line is lower and ARTEMIS is higher. Figure 9 shows the equivalent plot for the average negative acceleration plotted and average speed, which shows that the WSL cycles have less negative accelerations (*i.e.* the decelerations in the WSL cycles are not as rapid as those in the other cycles and driving patterns) and the ARTEMIS cycles have greater negative accelerations. The plots indicate that the WSL cycles are generally less 'aggressive' and the ARTEMIS sub-cycles slightly more 'aggressive' than driving patterns in the real world, although on whole the real-world driving cycles appear to be well-represented in the Reference Book and the UKEFD. A small number of UKEFD driving cycles appear to have average positive and negative accelerations which are outside the range of real-world conditions, though these are mainly the old TRRL cycles which were only used in one early test programme. The only important UKEFD outlier is the one at about 30 km h^{-1}, which is the MODEM7 cycle.

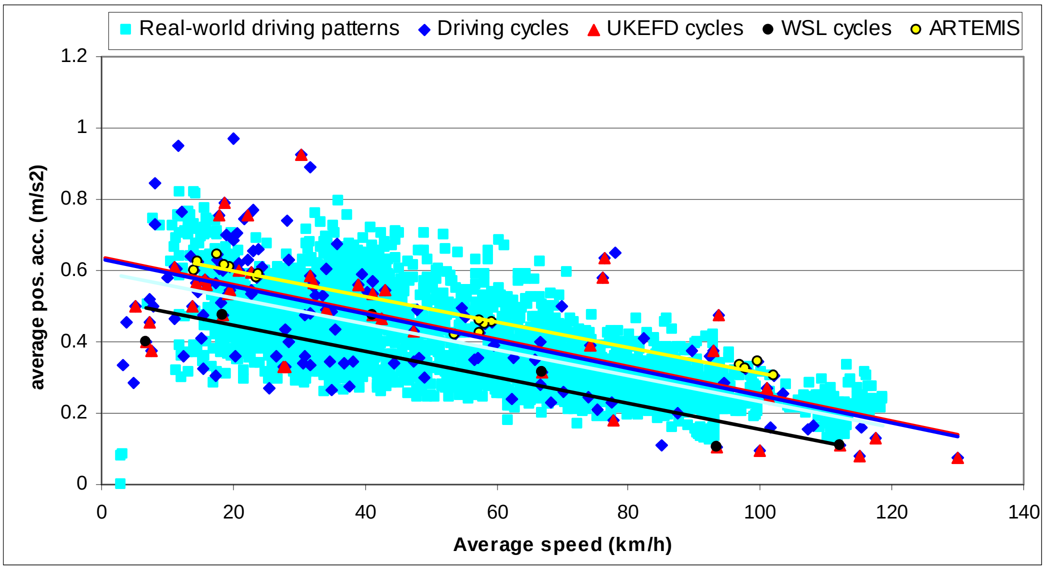

Figure 8: Average positive acceleration plotted against average speed – cars.

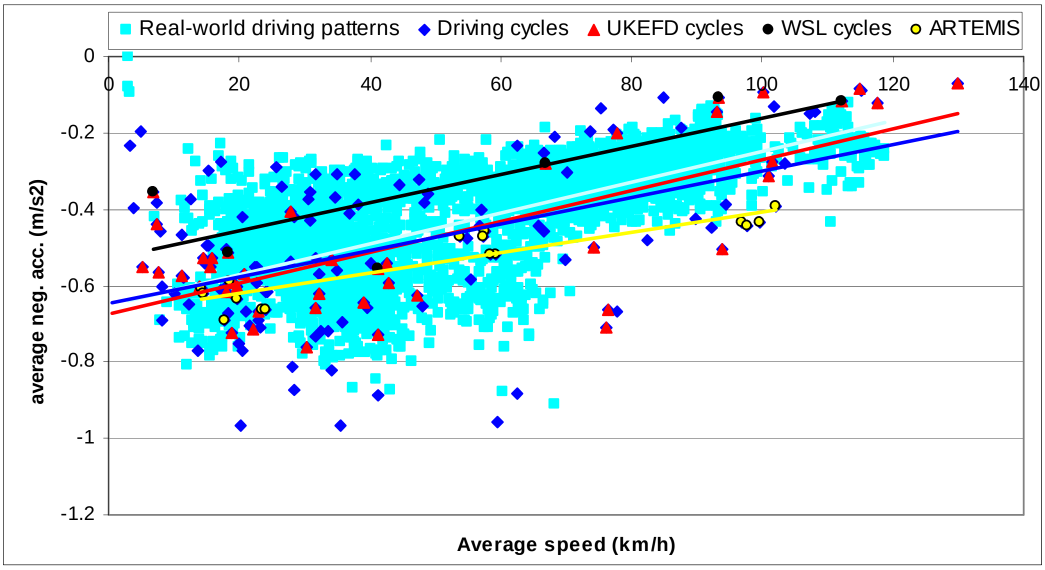

Figure 9: Average negative acceleration plotted against average speed – cars.

LGVs

Figure 10 shows the average speed distributions for LGVs. As mentioned earlier, the real-world data for LGVs relate principally to urban roads, and are therefore biased towards the lower end of the speed range and cannot be taken to be representative of UK conditions. This is apparent in the graph, with the real-world driving patterns being concentrated at the lower end of the speed range. The actual speed range of real-world driving is likely to be similar to that for cars shown in Figure 5.

As with cars, an assessment of cycle dynamics indicated that the WSL cycles were less aggressive than the real-world driving patterns, the driving cycles in the reference book and the UKEFD cycles. For example, Figure 11 shows the distributions of average negative acceleration, with the decelerations in the WSL cycles being less rapid than those in the other cycles and driving patterns.

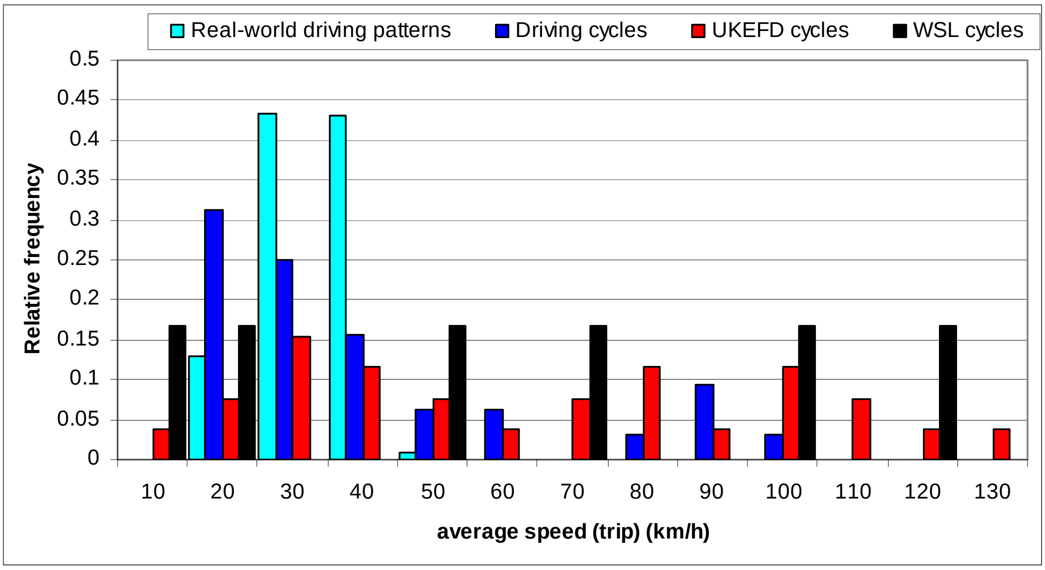

Figure 10: Distributions of average trip speed - LGVs

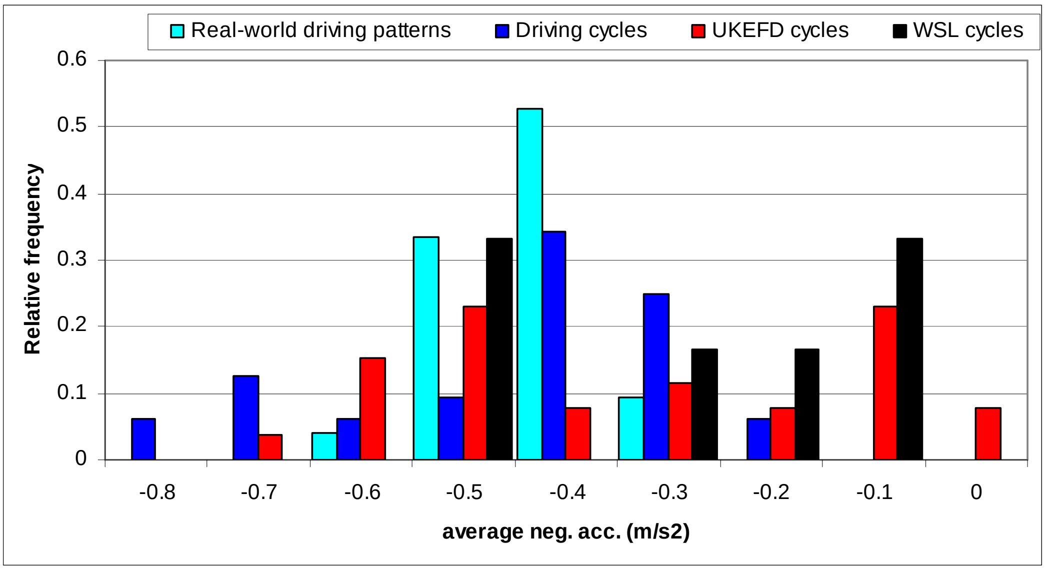

Figure 11. Distributions of average negative acceleration – LGVs.

HGVs

Figure 12 shows the distributions of average speed for the HGV driving patterns and cycles. Although some of the driving patterns, the Reference Book driving cycles and UKEFD cycles have average speeds lower than 10 km h^{-1}, such low average speeds are not represented in the FiGE cycle (which has a minimum average cycle speed of 23 km h^{-1}). The four data sets have broadly similar standard deviation distributions, as shown in Figure 13. However, there is a gap in the FiGE distribution between the medium and high values, and low standard deviations are not well represented.

Figure 14 shows average positive acceleration plotted against average speed for HGVs. Some of the low-speed Reference Book/UKEFD driving cycles have relatively high accelerations which are not apparent in the real-world driving patterns (specifically the Millbrook Heavy Duty: urban cycle and the three Millbrook Westminster Dust Cart cycles). The higher-speed FiGE cycles (suburban and motorway) also appear to have low average accelerations compared with the real-world driving patterns. From Figure 15 it can be seen that some of the UKEFD cycles have more rapid decelerations than the real-world driving patterns. In particular, one of the high-speed UKEFD cycles (Millbrook Heavy Duty: motorway) has a very high average deceleration, though this is likely to be due to one long deceleration at the end of the cycle (see Barlow *et al*., 2009). In addition, the higher-speed FiGE cycles have less rapid decelerations than the real-world driving patterns.

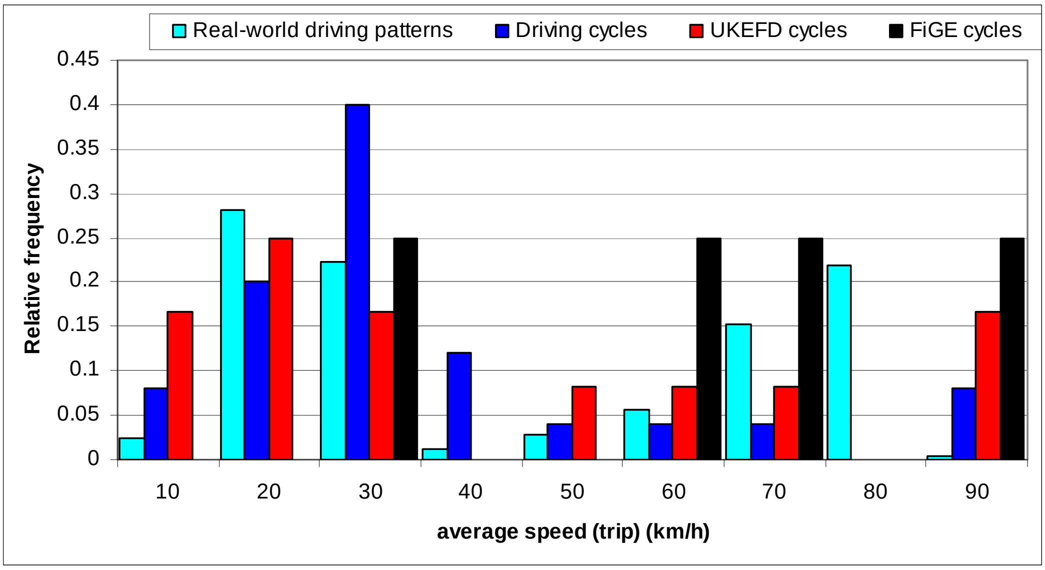

Figure 12. Distributions of average trip speed – HGVs.

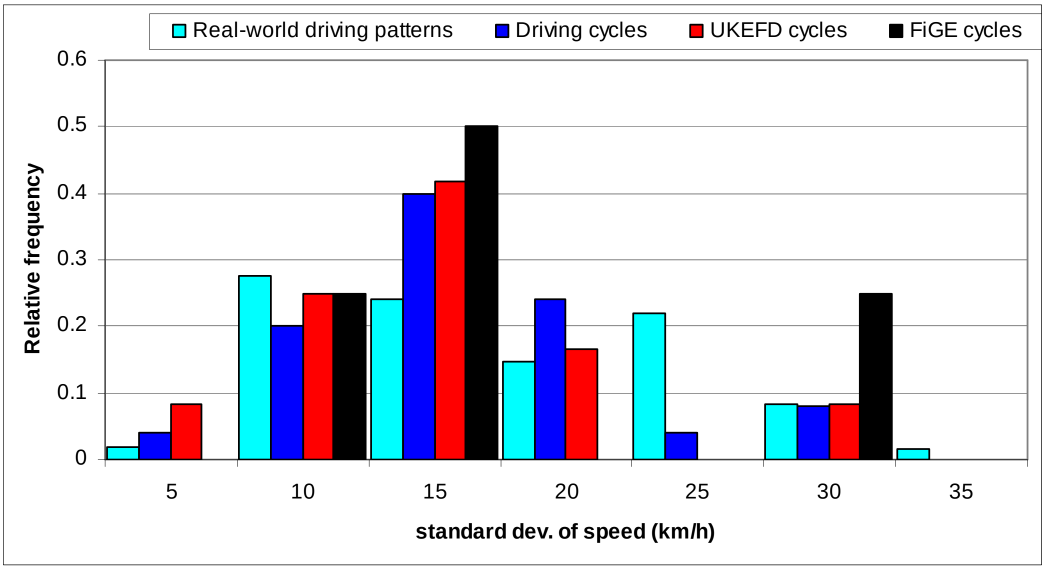

Figure 13. Distributions of standard deviation of speed – HGVs.

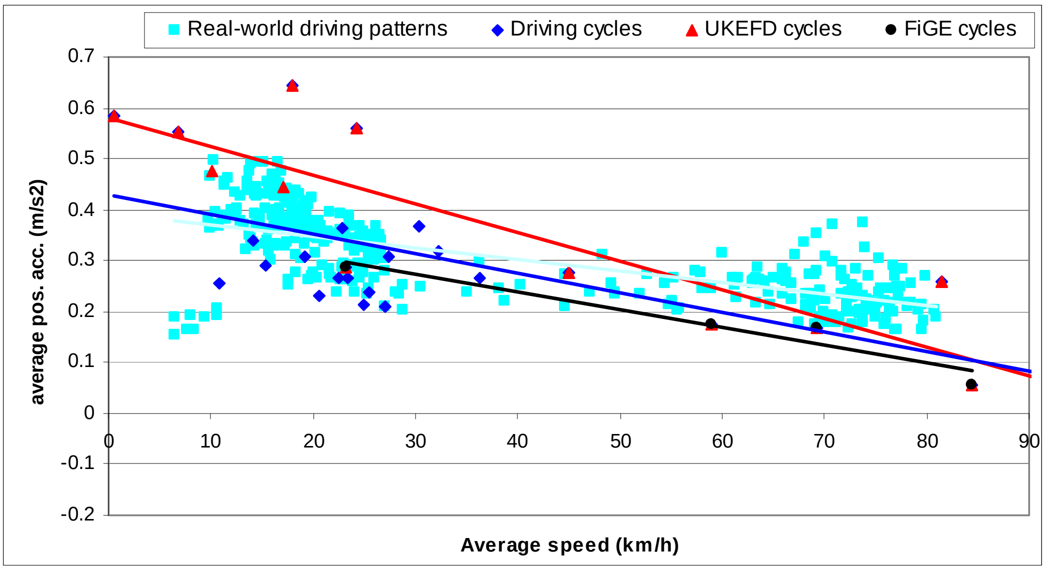

Figure 14. Average positive acceleration plotted against average speed – HGVs.

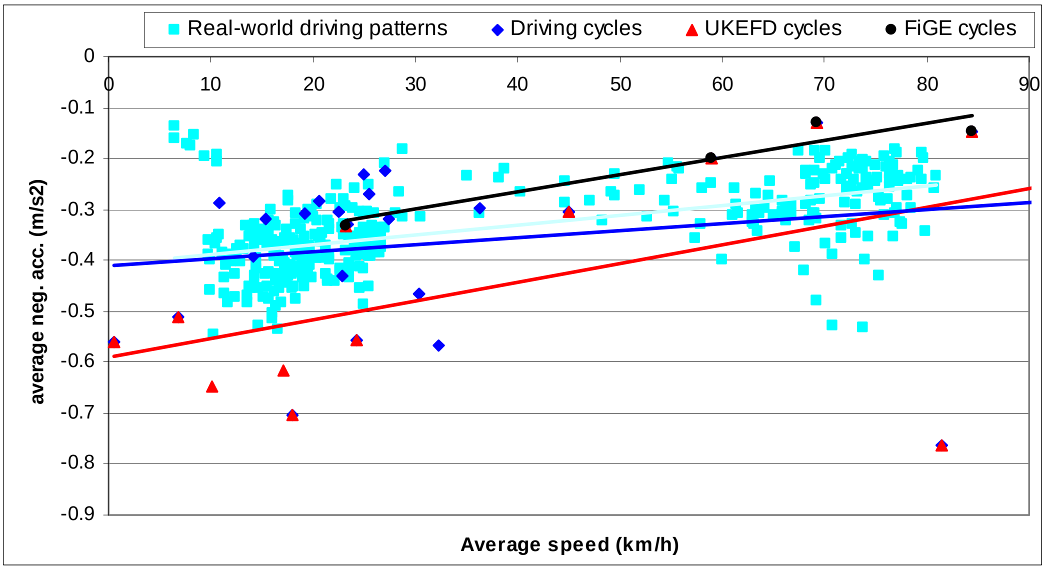

Figure 15. Average negative acceleration plotted against average speed – HGVs.

Buses and coaches

A single class of vehicles (‘Buses’) is used in the UKEFD to cover all buses and coaches. Figure 16 shows the distributions of average speed for buses. The Reference Book driving cycles have a similar distribution to the real-world driving patterns, although there is a small number of driving cycles with higher speeds. However, both the distributions for the UKEFD cycles and the FiGE cycles are biased towards higher speeds. Most of the real-world driving patterns for buses were logged on urban routes, and therefore have relatively low average speeds. Even rural buses are likely to have low average speeds. Urban buses may be unable to attain the higher speeds required for some of the cycles (including the motorway FiGE cycle). Coaches, on the other hand are likely to operate at higher motorway speeds, and do not generally have speed limiters fitted. Urban buses and coaches should therefore be treated separately when deriving emission factors, and more representative driving cycles for these vehicle classes should be used in the derivation of the future UK emission factors.

The distributions of average positive acceleration and average negative acceleration are shown in Figure 17 and Figure 18. The UKEFD and FiGE cycles clearly have lower accelerations and decelerations than the other two data-sets.

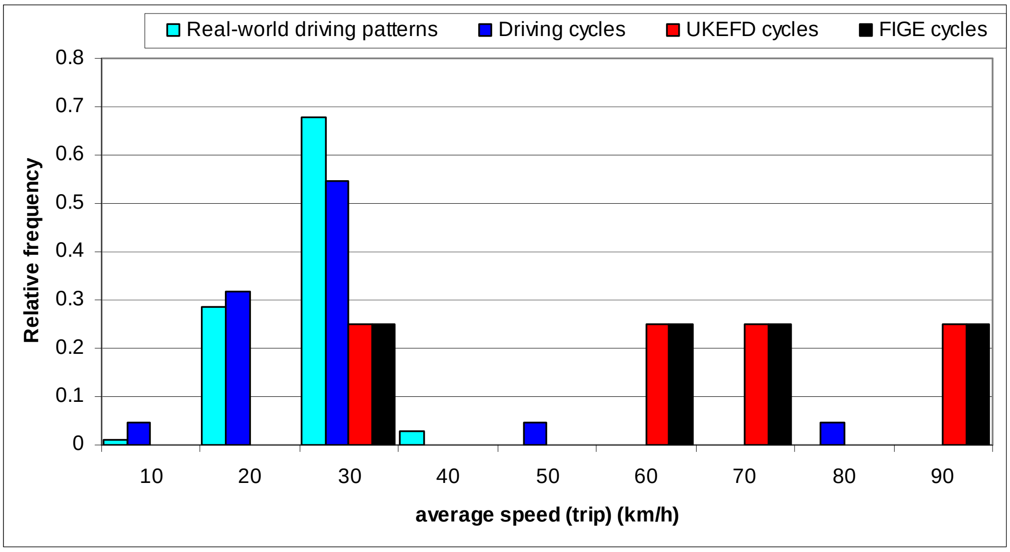

Figure 16. Distributions of average trip speed – buses

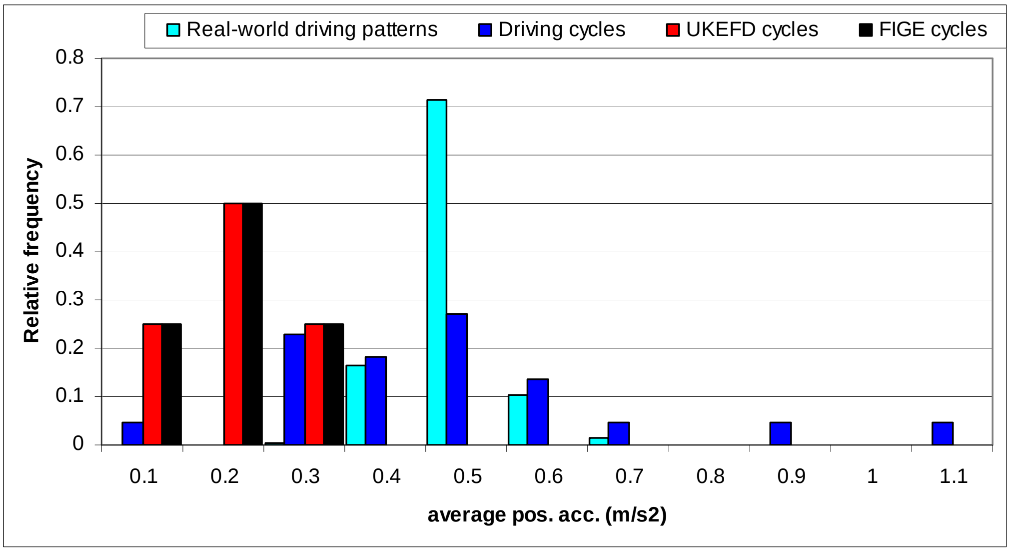

Figure 17. Distributions of average positive acceleration - buses

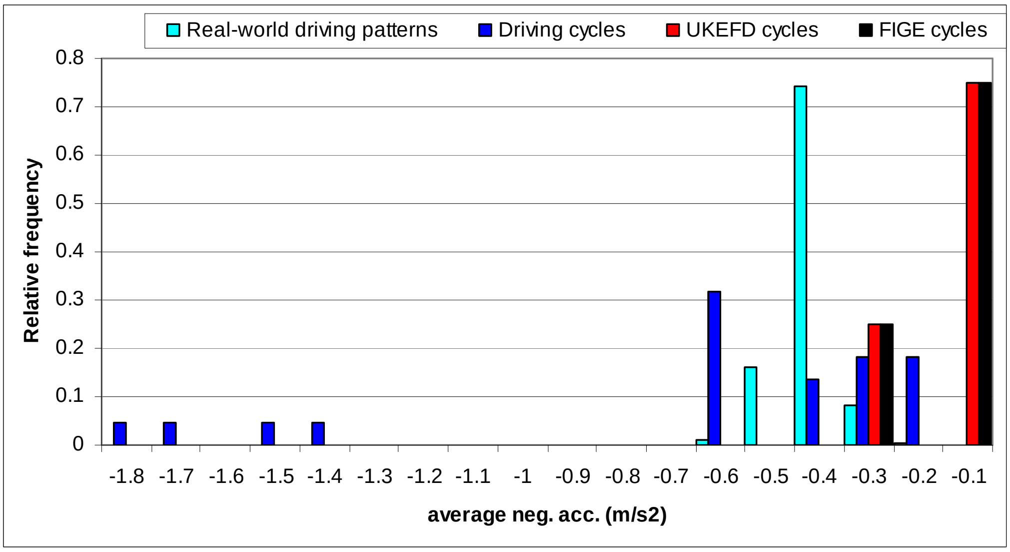

Figure 18. Distributions of average negative acceleration - buses

2.3.4 Summary

Most vehicles on urban roads are travelling at speeds which are between 20 mph (64 km h^{-1}) and 50 mph (80 km h^{-1}), and only a small proportion of vehicles are travelling at speeds below 20 mph. This implies that for inventory purposes the accurate characterisation of emissions at very low speeds is likely to be less important than accurate characterisation at higher speeds. However, it is important to note that accurate emission factors at low speeds remain important for local air quality assessment.

The real-world driving patterns, with all vehicle types included, have a large number of different average speeds, from just above zero to around 118 km h^{-1}, although the upper limit is restricted by the experimental design and it is clear that much higher speeds can actually occur. The driving cycles in the Reference Book and UKEFD cover a similar range of average speeds, but have a maximum average speed of 130 km h^{-1}.

For cars, the real-world driving patterns, the Reference Book driving cycles and the UKEFD cycles have broadly similar average speed distributions. The WSL and ARTEMIS cycles cover much of the speed range observed in the driving patterns, with only the highest speeds not being represented. The WSL cycles are generally less ‘aggressive’ than driving patterns in the real world, while the ARTEMIS sub-cycles were slightly more ‘aggressive’. On the whole, the real-world driving cycles appear to be well-represented in the UKEFD. The assessment of cycle dynamics for LGVs also indicated that the WSL cycles were less aggressive than the real-world driving patterns, the driving cycles in the reference book and the UKEFD cycles.

In the case of HGVs, although some of the driving patterns, the Reference Book driving cycles and UKEFD cycles have average speeds lower than 10 km h^{-1}, such low average speeds are not represented in the FiGE cycle. Furthermore, the FiGE cycles do not cover the highest speeds which could be reached with an unrestricted (pre-October 2001) HGV. Some of the low-speed Reference Book/UKEFD driving cycles have relatively high average accelerations and average decelerations which are not apparent in the real-world driving patterns. On the other hand, the higher-speed FiGE cycles appear to have lower average accelerations and decelerations than the real-world driving patterns.

A single class of vehicles (‘Buses’) is used in the UKEFD to cover all buses and coaches, even though buses and coaches tend to have different speed ranges. The Reference Book driving cycles have a similar average speed distribution to the real-world driving patterns. However, both the distributions for the UKEFD cycles and the FiGE cycles are biased towards higher speeds. The UKEFD and FiGE cycles clearly have lower accelerations and decelerations than the real-world driving patterns and the driving cycles in the Reference Book.

3 A review of emission test parameters

The second main element of Task 1 of the Project was a review of the parameters and data recorded during emission tests. The objective of this part of the work was to provide recommendations relating to how the usefulness of the recorded data might be improved, and which information should be routinely measured during testing. For example, in current tests the total mass emission of a pollutant is measured over a complete driving cycle. This allows emissions (in g km^{-1}) to be plotted as a function of average cycle speed. However, if only these parameters are recorded the data may be of limited use if there becomes a need to characterise emissions factors in terms other than g km^{-1} for an average speed.

3.1 Background

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

The first part of this review (Section 3.2) summarises the emission testing protocols which have been established for type approval in Europe. A large proportion of the existing emission data has been obtained during tests conducted in accordance with these protocols. However, their objective is not to assess the emissions of the European vehicle fleet but to ensure that compliance can be established for new vehicles (or engines) on an equal basis. Hence, the test conditions are standardised. In order to understand real-world emissions it is important to determine how variations in sampling conditions affect emission measurements. For cars, probably some of the most comprehensive examinations of the effects of different emission test parameters were those conducted as part of the ARTEMIS project (Joumard *et al.*, 2006a) and the PARTICULATES project (Samaras *et al*., 2005a). The results and conclusions from these studies are summarised in Section 3.3. The information for other types of vehicle is generally less extensive, although some of the ARTEMIS work on motorcycles and heavy-duty vehicles has been summarised in Sections 3.4 and 3.5.

3.2 European type approval procedures

In recognition of the contribution of vehicle emissions to air pollution, measures have been taken to reduce the quantities emitted. Since the early 1970s, limits have been applied to CO, HC and NO_x in vehicle exhaust. The limits have been reduced many times since they were first introduced, and changes have been made to the test method to make it more realistic and effective. All Member States within the EU are subject to the emission limits for road vehicles and engines, and methods of measurement are standardised in European legislation. Some aspects of the procedures were discussed in Section 2.1.1. Emissions of carbon dioxide from passenger cars, although not regulated, are controlled through voluntary agreements with the automotive industry[9].

For the purpose of emission standards and other vehicle regulations, vehicles are classified according to the categories listed in Table 9. Light goods vehicles (category N1) are further divided into three weight classes, as shown in Table 10.

[9] On 17 December 2008 the European Parliament voted to adopt a Regulation which limits the fleet average exhaust CO_2 emission from new cars to 130 g km^{-1}.

Table 9: Definition of vehicle categories (DieselNet, 2006).

Category	Description
L	Two- and three-wheel vehicles.
M	Motor vehicles with at least four wheels designed and constructed for the carriage of passengers.
M_1	Vehicles comprising no more than eight seats in addition to the driver's seat.
M_2	Vehicles comprising more than eight seats in addition to the driver's seat, and having a maximum mass not
M_3	Vehicles comprising more than eight seats in addition to the driver's seat, and having a maximum mass
N	Motor vehicles with at least four wheels designed and constructed for the carriage of goods.
N_1	Vehicles having a maximum mass not exceeding 3.5 tonnes.
N_2	Vehicles having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes.
N_3	Vehicles having a maximum mass exceeding 12 tonnes.
O	Trailers (including semi-trailers).
G*	Off-Road Vehicles.

* For off-road vehicles the symbol G is combined with either symbol M or N. For example, a vehicle of category N_1 which is suited for off-road use is designated as N_1G.

Table 10: Weight classes for vehicle category N_1.

Class	Reference weight (RW)	
	Euro 1-2	Euro 3+
I	RW ≤ 1250 kg	RW ≤ 1305 kg
II	1250 kg < RW ≤ 1700 kg	1305 kg < RW ≤ 1760 kg
III	1700 kg < RW	1760 kg < RW

3.2.1 Light-duty vehicles

Background

European Union emission regulations for new light-duty vehicles (cars and light goods vehicles) are specified in the Directive 70/220/EEC. This Directive has been amended a number of times, with some of the most recent amendments including:

- Euro 1 standards (1992) - Directives 91/441/EEC (cars) and 93/59/EEC (cars and light trucks)
- Euro 2 standards (1996) - Directives 94/12/EC and 96/69/EC
- Euro 3 standards (2000) - Directive 98/69/EC
- Euro 4 standards (2005) - Directive 98/69/EC
- Euro 5 standards (2009) - Regulation EC 692/2008
- Euro 6 standards (2014) - Regulation EC 692/2008

At the Euro 2 stage separate emission limits were introduced for diesel and petrol vehicles.

Petrol vehicles are exempt from the standards for PM up to the Euro 4 stage.

The Euro 5 and Euro 6 standards were recently adopted and the limit values may be found in Tables 1 and 2 of Annex XVII to Regulation EC No 692/2008[10]. The earliest compliance date for type approval will be September 2009. The Euro 5 stage includes PM standards for direct-injection petrol cars, and a particle number emission limit of 6×10^{11} km^{-1} is also mandated for all diesel vehicles.

[10] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:199:0001:0136:EN:PDF

Fuels

The 2000/2005 standards were accompanied by the introduction of more stringent fuel regulations, requiring a minimum diesel cetane number of 51 (2000), a maximum diesel sulphur content of 350 ppm in 2000 and 50 ppm in 2005, and a maximum petrol sulphur content of 150 ppm in 2000 and 50 ppm in 2005. ‘Sulphur-free’ diesel and petrol fuels (≤ 10 ppm sulphur) had to be available from 2005, and became mandatory from 2009.

Emission testing procedure

For light-duty vehicles the tests are performed on a chassis dynamometer, as briefly summarised in Section 2.2.1. Further details of the test procedure are given below.

Emissions are measured over the NEDC (see Figure 1), which is comprised of a low-speed urban part (ECE15) with four segments (also known as the Urban Driving Cycle, or UDC), and a high-speed part known as the Extra-Urban Driving Cycle (EUDC). The ECE15 is characterised by low vehicle speed, low engine load, and low exhaust gas temperature. The EUDC includes more aggressive driving modes. The maximum speed of the EUDC cycle is 120 km h^{-1}. The four ECE segments are repeated without interruption, and are followed by one EUDC segment. Before the test, the vehicle is allowed to soak for at least six hours at a temperature of 20-30°C. Prior to the introduction of the Euro 3 standard in 2000, the vehicle was then started and allowed to idle for 40 seconds before sampling began. However, with the introduction of Euro 3 the idling period was eliminated, and sampling began at engine start.

The vehicle exhaust gases are diluted with filtered air to prevent condensation or reactions between the different exhaust gas components. The dilution takes place in a tunnel known as a ‘constant volume sampler’ (CVS). The system maintains a constant volumetric flow, controlled by a critical flow venturi, a critical-flow orifice or a positive displacement pump. During the emission test a sample of the diluted exhaust gas is drawn from the dilution tunnel and collected in a pair of Tedlar sampling bags (sometimes, multiple pairs of bags are used to give results for sub-segments of the cycle). One bag is used for the diluted exhaust gas and the other for the dilution air. The latter is used for correction, since the dilution air may also contain small amounts of the compounds being measured. After the test, the content of each Tedlar bag is analysed. The analysis of the regulated exhaust gases and CO_2 is quite straightforward, and is extensively described in the various Directives. Dedicated analysers are used for CO, NO_x, HC and CO_2. The CO and CO_2 analysers operate by non-dispersive infrared (NDIR). The HC analyser operates by flame ionisation detection (FID) and the NO_x analyser by chemiluminesence. Multiplication of the concentration of a given pollutant by the tunnel air flow gives the emission factor in grammes per kilometre. Again, the calculation procedure is extensively described in the European Directives.

For diesel vehicles only, PM is collected separately from the other emission components by drawing diluted exhaust gas from the tunnel through a pair of Pallflex filters. The second filter serves to detect and, if necessary, to correct for any sample breakthrough from the first filter. The filters are weighed before and after the test (in both cases, following a period of conditioning under a specified temperature and humidity ranges) and their weight increase is used to determine the PM mass emission factor.

For Euro 5 and Euro 6 diesel vehicles particle number emissions are measured according to the procedure developed by the Particle Measurement Programme (PMP). Only solid particles are counted, as volatile material is removed from the sample in the PMP procedure. The proposed numerical limit reflects the technical capabilities of diesel engines fitted with particulate filters.

No limit values are defined for CO_2, although the CO_2 concentration is also determined, as is used in the calculation procedure. The CO_2 emission value is also used to calculate the fuel consumption (in l/100km) using the carbon balance method.

3.2.2 Heavy-duty vehicles

Background

The European emission standards apply to all motor vehicles with a ‘technically permissible maximum laden mass’ of more than 3,500 kg, equipped with compression ignition, positive ignition natural gas or LPG engines. This covers a wide range of vehicles, and the engine and the body are usually built by separate companies. In order to avoid the complexity and cost of a separate type approval procedure for all varieties of vehicle, the responsibility for compliance with emissions regulation is borne by the engine manufacturer.

The regulations for heavy-duty engines were originally introduced by the Directive 88/77/EEC, followed by a number of amendments. Some of the most recent amendments include the following (the dates for compliance are given in brackets):

- Euro I standards (1992) - Directive 91/542/EEC
- Euro II standards (1996) - Directive 91/542/EEC
- Euro III standards (2000) - Directive 1999/96/EC
- Euro IV/V standards (2005/2008) - Directive 1999/96/EC
- Euro VI standards (2013) - proposed in COM(2007)851

Test procedure

The first Directive applicable to heavy-duty diesel engines was a restriction on visible smoke (Directive 72/306/EEC). This was determined using a ‘free acceleration smoke’ (FAS) test. The first limits on mass emissions of gaseous pollutants were introduced by Directive 88/77/EEC, which set standards for carbon monoxide (CO), total hydrocarbons (THC) and NO_x based on the ECE-R49 test. The ECE-R49 is a 13-mode steady-state test cycle, introduced by ECE Regulation No.49 and then adopted by the EEC Directive 88/77. It was used for type approval up to and including Euro II level. The test is normally performed on an engine dynamometer, with the engine being operated through a sequence of 13 engine speed and engine load conditions, and for a prescribed time in each mode. The exhaust emissions measured during each mode are expressed in g/kWh, and the final test result is a weighted average of the 13 modes.

The ESC (European Stationary Cycle, also known as OICA/ACEA cycle) was introduced, together with the ETC (European Transient Cycle) and the ELR (European Load Response) test, for emission certification of Euro III heavy-duty diesel engines in October 2000. The ESC replaced the ECE-R49 test, and is also a 13-mode steady-state procedure. The ELR engine test, which consists of a sequence of load steps at constant engine speeds, was introduced for the purpose of smoke opacity measurement.

The ETC test cycle (also known as FiGE cycle) was introduced alongside the ESC for emission certification of heavy-duty diesel engines in Directive 1999/96/EC. The FiGE Institute developed the cycle in two variants, as a chassis and an engine dynamometer test, though for the purpose of engine certification the ETC cycle is performed on an engine dynamometer. Different driving conditions are represented by three parts of the ETC cycle. Part one represents city driving with a maximum speed of 50 km/h, and includes frequent starts, stops, and idling periods. Part two represents rural driving, begins with a steep acceleration segment, and has an average speed of 72 km h^{-1}. Part three represents motorway driving with an average speed of 88 km h^{-1}.

The European Commission published a proposal for Euro VI emission standards in December 2007 (COM(2007)851). This was adopted by the European Parliament on 16 December 2008, but has not yet been published in the Official Journal of the European Union. In addition to introducing more stringent emission limits, the Regulation includes a limit of 10 ppm for NH_3, which can be emitted due to the use of additive-based emission control systems. A particle number limit is also planned in addition to the mass-based limit, pending the results of the UN/ECE Particulate Measurement Programme. The compliance date for Euro VI will be during 2013.

3.2.3 Two-wheel vehicles

Due to the regular introduction of new legislation and the tightening of the limits for CO, HC, NO_x and PM, the absolute emission levels of passenger cars and HDVs have reduced significantly. There have been fewer changes in the legislation relating to two-wheel vehicles. Stage 1 (‘Euro 1’) of Directive 97/24/EC, which became effective in 1999, introduced more stringent limits than the existing ECE R40 Regulation. In 2003, stage 2 (Euro 2) of 97/24/EC entered into force. This reduced the limits again without changing the type approval test cycle. For 2006 (Euro 3) the emission limits are lower still, and the type approval test cycle has been changed. The ECE-R40 cycle (four urban cycles) has been replaced by a combination of the UDC and EUDC cycles used for passenger cars. Manufacturers and certified agencies are also allowed to use the World Harmonised Type Approval Cycle (WMTC) for type approval.

3.3 Effects of different test parameters: cars

3.3.1 Background

This Section of the Report describes the work conducted in ARTEMIS on exhaust emissions from passenger cars. The Section is a summary of the main technical reports on the subject (Joumard *et al*., 2006a, 2006b).

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

(i) An investigation of the measurement differences between laboratories

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

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

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

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

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

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

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

These parameters were divided into four main categories:

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

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

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

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

3.3.2 Experimental work

A reference set of real-world driving cycles was developed in order to improve the representativeness of emission tests and the comparability of the measurements made in different laboratories. Three main real-world driving cycles - 'urban', 'rural', and 'motorway' - were constructed to represent driving according to the respective area/road types. Two versions of the motorway cycle were produced, one with a maximum speed of 150 km h^{-1} and one with a maximum speed of 130 km h^{-1}. The latter was developed for use on emission testing facilities which are not capable of operating at the higher speed. Some of the cycles also included a 'pre-' or 'post-' phase to allow trip start and end conditions to be defined. Different gear-shift strategies were also reviewed, with a simplified approach being adopted for ARTEMIS (André, 2004). The main ARTEMIS cycles, including a number of sub-cycles, are shown in Figure 19.

As the ARTEMIS driving cycles were constructed using representative real-world driving patterns, it is possible to estimate emissions for a wide range of traffic situations by combining and weighting the cycles and sub-cycles. A statistical approach of this kind is described by André (2004). The ARTEMIS cycles are now used extensively in European research projects and national programmes for the measurement and modelling of pollutant emissions.

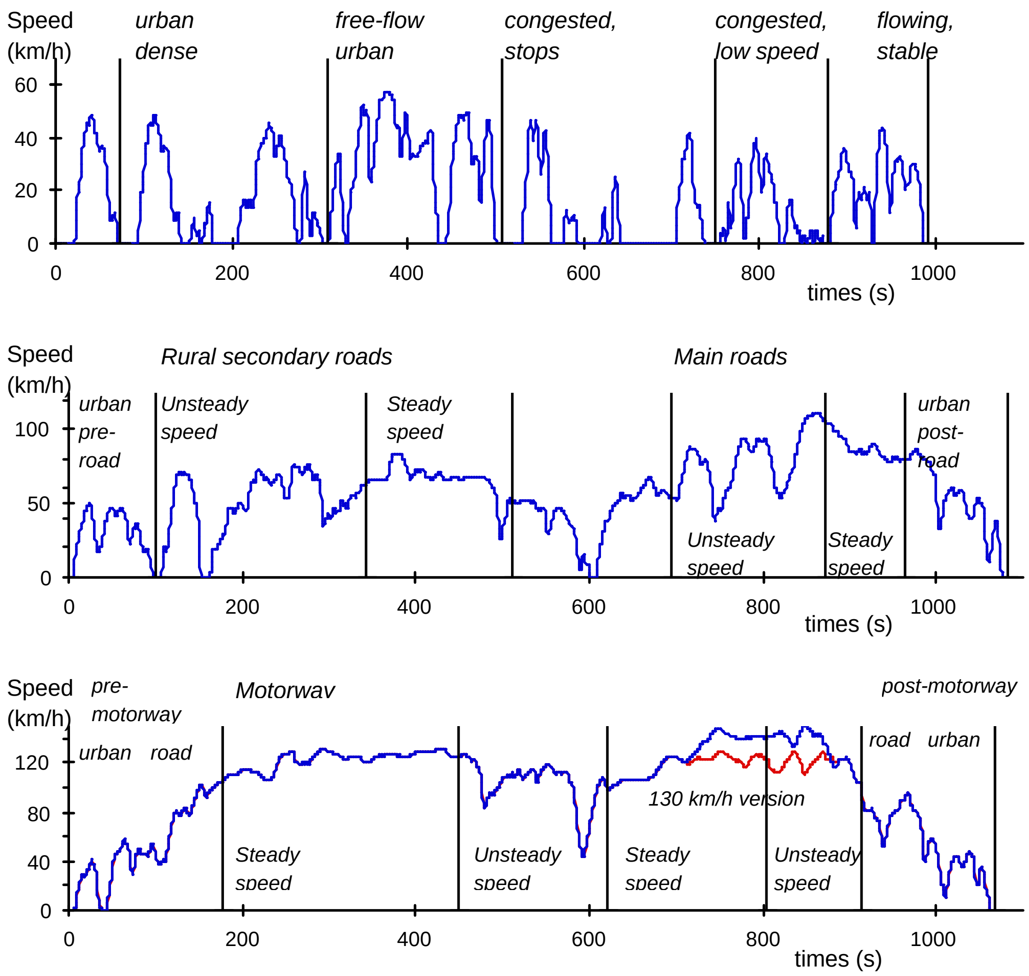

Figure 19: The ARTEMIS urban, rural and motorway driving cycles, including sub-cycles and starting conditions (André, 2004).

Emission tests were conducted at each of the nine participating laboratories using a chassis dynamometer. The fuels used during the tests were obtained from local petrol stations. The regulated pollutants (CO, HC, NO_x and PM) and CO_2 were collected using a constant volume sampler (CVS). Pollutants were collected as bag or filter samples, and were also usually measured continuously. Standard analytical techniques were used (NDIR for CO and CO_2, chemiluminescence for NO_x, flame ionisation detection for HC, and filter weighing for PM), fuel consumption was calculated using the carbon balance method.

The actual parameters studied in ARTEMIS are summarised in Table 11. A separate programme was designed for each parameter except the vehicle sampling method. The vehicle sample sizes for each task are listed by fuel and emission standard in Table 12. It was also considered necessary to compare the laboratories by performing a ‘round robin’ test with a single reference vehicle.

A total of 183 vehicles were tested during the ARTEMIS project. The detailed characteristics of all the test vehicles are given by Joumard *et al*. (2006a). In total, 2,753 tests were carried out, of which:

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

The studies of the individual parameters, including the method used and the results obtained, are briefly summarised in Sections 3.3.3 to 3.3.6. The tests are described in detail in dedicated reports compiled for each parameter studied, and references to these reports can be found in the relevant Sections. The methodology for the round robin test programme is summarised in Section 3.3.7.

Table 11: Parameters studied, with an indication of the approach used (Joumard *et al*., 2006a)

Type of parameter	Parameter	Literature review	Reprocessing of old data	New tests
Driving behaviour	Driving cycle	✓	✓	✓
	Gear-shift behaviour			✓
	Influence of the driver		✓	
Vehicle-related	Technological characteristics	✓		✓
	Emission stability			✓
	Emission degradation	✓		✓
	Fuel properties	✓		✓
	Cooling fan operation			✓
	Vehicle preconditioning			✓
Vehicle sampling	Method of vehicle sampling	✓		
	Vehicle sample size	✓	✓	
Laboratory-related	Ambient temperature			✓
	Ambient humidity			✓
	Dynamometer settings			✓
	Dilution ratio			✓
	Sample line temperature			✓
	PM filter preconditioning			✓
	Response time	✓		✓
	Dilution air conditions			✓
Round robin test				✓

Table 12: Vehicle samples per parameter - vehicles in brackets were tested in former research projects, or represent a sub-sample for more detailed analyses (Joumard *et al*., 2006a)

	Parameter	Total	Petrol						Diesel					
			Pre-Euro 1	Euro 1	Euro 2	Euro 3	Euro 4	Total	Pre-Euro 1	Euro 1	Euro 2	Euro 3	Euro 4	Total
Driving	Driving cycle	33*(9)*		3	7	6*(4)*		16*(4)*	2	3*(2)*	10*(2)*	2*(1)*		17*(5)*
	Gear-shift behaviour	15		3	3	2		8		2	4	1		7
	Influence of the driver	*1*		*1*				*1*						*0*
Vehicle	Tech'cal characteristics	43*(13)*			3	23*(5)*[a]	6*(3)*[a]	32*(8)*[b]			2	9 *(5)*		11*(5)*
	Emission stability	12		1	3	6		10				2		2
	Emission degradation	2				2		2						0
	Fuel properties	2				1		1				1		1
	Cooling fan operation	6			4			4			1	1		2
	Vehicle preconditioning	5			2	1		3			2			2
	Vehicle sample size	*80*	*34*	*18*	*3*			*55*	*11*	*9*	*5*			*25*
Laboratory	Ambient temperature	31	6		7	7	2	22			8	1		9
	Ambient humidity	11			4	5		9			2			2
	Dynamometer settings	5			3			3			2			2
	Dilution ratio	8			2	1		3			3	2		5
	Sample line temperature	1						0			1			1
	PM filter preconditioning	1						0				1		1
	Response time	5	1	1	1			3			1	1		2
	Dilution air conditions	2			1		1	2						0
Round robin tests		1				1		1						0
Total		183	7	8	40	55	9	119	2	5	37	20	0	64

a including one CNG vehicle
b including two CNG vehicles

3.3.3 Driving behaviour parameters

Driving cycle

The aims of this part of the work were to review and compare existing passenger car driving cycles in relation to their kinematics, their representativeness and their method of development, and to determine the sensitivity of emission measurements to driving cycle characteristics. As far as the relationship between emissions and driving cycle characteristics was concerned, the three specific objectives were:

- To identify the kinematic parameters that would enable detailed modelling of emissions.
- To harmonise and analyse the complex and varied dataset of passenger car emission factors collected within ARTEMIS, with measurements having been conducted over a wide range of driving cycles.
- To establish an emission modelling approach that could be used at the 'street' level.

The work was conducted in three stages:

Stage 1: Analysis of the ARTEMIS driving cycle database for passenger cars.

Stage 2: Analysis of data from an experiment dealing with low-powered and high-powered cars.

Stage 3: Analysis of the full ARTEMIS emission factor database for passenger cars.

<u>Stage 1: Analysis of the ARTEMIS driving cycle database</u>

The first stage of the analysis involved the collection and review of 213 different real-world passenger car driving cycles or sub-cycles (André *et al.*, 2006). These cycles were characterised in terms of their kinematic content - principally a two-dimensional distribution of the instantaneous speed and acceleration. Due to the wide variation in driving cycle dynamics a pre-classification of the cycles was considered necessary. A smaller sample of 14 different cycles was therefore selected for this purpose. These 14 driving cycles included the main ARTEMIS cycles, cycles used in HBEFA and cycles from Napoli, and their detailed characteristics are given by Joumard *et al*. (2006a). The cycles were tested on a sample of nine petrol and diesel passenger cars. In Figure 20, the cycles (and sub-cycles) are characterised according to their mean driving speed and average positive acceleration. This enabled the identification of three different cycle categories which were associated with distinctly different driving behaviour: (i) urban, (ii) suburban/rural and (iii) main roads/motorways. Finally, for each of these three main cycle categories, eight different sub-categories were defined. The sub-categories related to more subtle differences in the type of driving. The findings for Euro 2 and Euro 3 vehicles are summarised in Table 13.

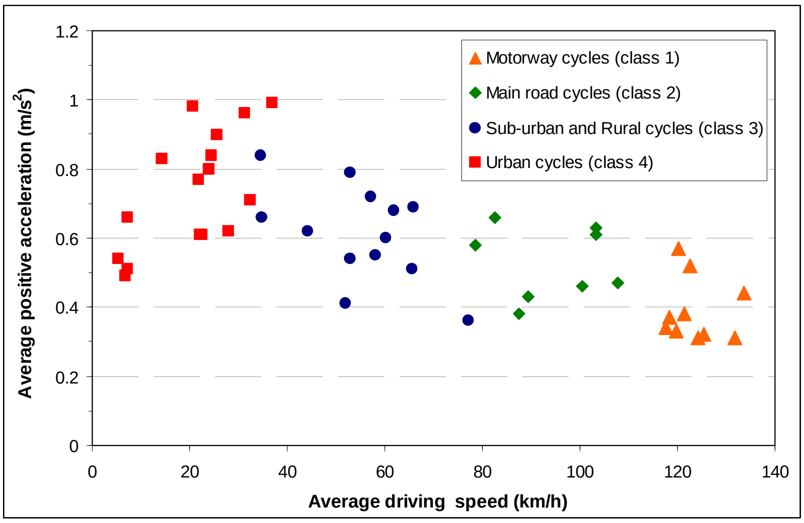

Figure 20: Final selection of the cycles and corresponding sub-cycles and their coverage as regards running speed and acceleration.

Table 13: Effects of driving type on emissions from Euro 2 and Euro 3 petrol and diesel cars.

Vehicle type	Driving type	Observations
Diesel	Urban	Emissions of all pollutants increase with stop frequency and relative stop duration.
		Emissions of all pollutants except CO decrease as speed increases. CO emissions are sensitive to high speeds (60-100 km h^{-1}).
		NO_x and CO_2 emissions are sensitive to the frequency and strength of accelerations.
	Rural	Emissions of all pollutants increase with stop frequency and relative stop duration.
		Emissions of all pollutants decrease as speed increases, and are sensitive to low speed (<20-40 km h^{-1}) and to acceleration. CO is sensitive to the maximum acceleration or deceleration.
	Motorway/ main road	NO_x and CO_2 emissions are sensitive to high speeds (120-140 km h^{-1}) and to the variation in speed (standard deviation of the speed), but emissions decrease at intermediate speeds (60-100 km h^{-1}).
		CO emissions increase with the occurrence of intermediate or low speeds, of stops, and of accelerations, and are low at high speeds.
Petrol	Urban	Emissions of all pollutants are sensitive to acceleration (mean, frequency, strength, time spent at high accelerations).
		CO and HC emissions are sensitive to high speeds (60-100 km h^{-1}) and strong accelerations.
		Emissions of CO_2 and HC increase with the number of stops. CO_2 decreases as the speed increases.
	Rural	Emissions of all pollutants are sensitive to acceleration (mean, frequency, strength, time spent at high accelerations).
		Emissions of CO_2, HC and NO_x increase with the stops duration and frequency.
		Emissions of CO_2 and NO_x decrease as the speed increases.
	Motorway/ main road	Emissions of all pollutants are sensitive to accelerations at high speeds. CO_2 and CO are high at high speeds (120-140 km h^{-1} and above) and low at intermediate speeds (60-100 km h^{-1}).

The findings stated in Table 13 only relate to Euro 2 and Euro 3 vehicles, and were not used in the development of the ARTEMIS model. Consequently, their validity for Euro 4 (and later) vehicles was not examined. It is unlikely that the findings will hold for the most modern vehicles because of different responses of after-treatment technologies to driving conditions. For the whole dataset, the fuel type (petrol, diesel), the emission standard, the main driving type (urban, rural, motorway/main road) and driving cycles, and the vehicle itself were identified as the most important factors. However, the variation associated with the main driving type or cycle was greater than the variation associated with the other factors. This highlights the important effect of the driving cycle on emissions. For diesel cars it appeared that the driving type, the driving cycle and the vehicle itself were the most important factors determining emissions, whereas for petrol cars the vehicle and the emission standard were the most important factors. A clear contrast was observed between the emission behaviour of diesel vehicles, which were rather sensitive to speed and stop parameters, and petrol cars, which were rather sensitive to accelerations. There was also a certain similarity between the effects of urban and rural driving for both the categories of vehicle. The analysis for Euro 2 and Euro 3 vehicles demonstrated that urban congested driving with many stops resulted in high CO_2 emissions for petrol and diesel cars, and high NO_x emissions for diesel cars. During motorway driving, stable high speeds (*e.g.* ARTEMIS motorway, 150 km h^{-1}, 'steady speed' – see Figure 19) generated high CO_2 emissions, whilst unstable high speeds (*e.g.* ARTEMIS motorway, 150 km h^{-1}, 'unsteady speed') led to higher NO_x emissions from diesel cars and higher CO emissions from petrol cars.

<u>Stage 2: Analysis of data for low-powered and high-powered cars.</u>

Driving cycle characteristics were investigated for cars having different engine power ratings. The objective of the study was to examine the differences in emissions between using (i) a generic test cycle for all vehicles, and (ii) vehicle-specific driving cycles. The ARTEMIS cycle was used as the generic cycle. The specific cycles were derived using the same database and principles as the ARTEMIS cycle, but considered two classes of vehicle according to power:mass ratio (low-powered cars with 61 W/kg or less, and high-powered cars with more than 61 W/kg) and urban, rural and motorway driving conditions (André, 2004). A sample of 30 cars from the French fleet was used in the tests.

The analysis demonstrated that the use of a generic test procedure (as in ARTEMIS) could lead to very different emissions estimates, particularly for the most recent vehicle categories. For Euro 2 and 3 vehicles the use of the generic driving cycles led to significant errors in the emission factors. CO emissions from petrol cars were under-estimated by 15-20%. For diesel cars, emissions of HC and PM were under-estimated, and CO emissions were over-estimated by 20%. The level of under- or over-estimation depended upon the driving type and the test procedure. Indeed, the use of the generic cycles led to a significant over-estimation of emissions for urban driving (6-10% for NO_x and CO_2, 15-20% for CO and HC), whilst emissions for rural and motorway driving were slightly under-estimated. Finally, it was found that for low-powered cars, CO_2 emissions and fuel consumption were higher (by 11 %) when measured using the generic cycles than when measured using more appropriate cycles. The generic procedure also led to an under-estimation of CO and HC emissions for small cars (by 4-13%) and a slight over-estimation of HC and NO_x from the most powerful cars (10%). Consequently, in the future consideration should be given to the use of vehicle-specific driving cycles to allow pollutant emissions to be measured more accurately.

<u>Stage 3: Analysis of the full ARTEMIS emission factor database for passenger cars</u>

The third set of emission data considered in the assessment was the whole ARTEMIS emission factor database (all tests for which a driving cycle was available). The ARTEMIS database included tests from more than 20 European laboratories, and covered measurements from 1980 to 2004. It included 2,800 cars in most of the European legislative categories, 800 different cycles or sub-cycles, and 27,000 emission tests. From this database, 20,000 emission tests were analysed, covering 217 cycles and 158 sub-cycles. The main purpose of this work was to standardise the database in relation to the driving cycle, before the generation of the final ARTEMIS emissions factors, and to develop a suitable modelling approach for use at the street level.

The emissions data obtained using the ARTEMIS cycles were analysed by fuel type, emission regulation and engine size. Taking into account the test number per category, three diesel car classes (Euro 1, 2, 3) and seven petrol car classes (Euro 1, Euro 2 1.1-1.4 l, Euro 2 > 1.4 l, Euro 3 1.1-1.4 l, Euro 3 1.4-2.0 l, Euro 3 > 2.0 l, Euro 4) were investigated. A hierarchical model was constructed to explain the logarithm of the total emission per cycle, as a function of the cycle characteristics. It is not common practice to use the logarithm of the emission - this was justified by the fact that emissions were close to zero with a large coefficient of variation, and because emission results are generally distributed according to a log-normal distribution. It would be of interest to test the application of this approach in the development of the UK emission factors. The resulting 'high-level' model combined two individual partial-least-square regression models based on the different sets of kinematic parameters (termed 'low-level' models). The first low-level model was based on seven dynamics-related parameters (average speed, square and cubic speed, idling and total running times, the average of the speed-acceleration product, and the reciprocal of the cycle distance). The second low-level model considered the two-dimensional distribution of the instantaneous speed and acceleration. These low- and high-level models were compared with a traditional polynomial regression model. The results demonstrated once again that the driving cycle is a predominant factor affecting emissions, and that engine size is a significant factor for CO_2 emissions from petrol cars.

For the low-level models the best fit between the observed and predicted emissions was usually obtained using the model based on the distribution of the instantaneous speed and acceleration, although the dynamics-related model produced satisfactory results for CO_2 from Euro 1 diesel cars. The high-level model resulted in a slightly better prediction. The average speed model was unable to predict the trends in emissions, and led to an over-prediction of emissions at high speeds. The model fit was generally good for CO_2 but less satisfactory for the other pollutants due to a large variability between vehicles.

The significant influence of the driving conditions on the emissions implied the need to apply a driving cycle correction to the emission factors in the ARTEMIS database prior to modelling. An approach based on kinematic similarity was developed, and this consisted of three main steps:

(i) Grouping of cycles by kinematic content through the construction of a classification scheme.
(ii) Selection of appropriate cycles to represent each group.
(iii) The determination of corrections to develop reference emission factors.

More than 800 cycles and sub-cycles were included in the ARTEMIS database, of which 375 were relevant to this part of the work. The full driving cycles, but not the sub-cycles, are described by André (2006). The most important driving cycles in the database – the 98 cycles or sub-cycles for which there were significant numbers of emission test results - were used to develop the cycle classification scheme. The other cycles were not used in the construction of the scheme, but were classified according to it.

The classification scheme was based upon the two-dimensional distribution of the average driving speed and acceleration (Figure 21). A factorial analysis and an automatic clustering procedure were applied to identify distinct classes by maximising the homogeneity within classes and the contrast between classes. The resulting 15 classes were termed 'Reference Test Cycles' (RTCs). Thirteen of the RTCs were combinations of the ARTEMIS cycles and sub-cycles. The two others represented very congested driving and stable motorway driving (Table 14). For each vehicle category and pollutant, an emission factor was allocated to each RTC (Joumard *et al.*, 2006a). RTCs can be combined in order to compute emissions for any traffic situation.

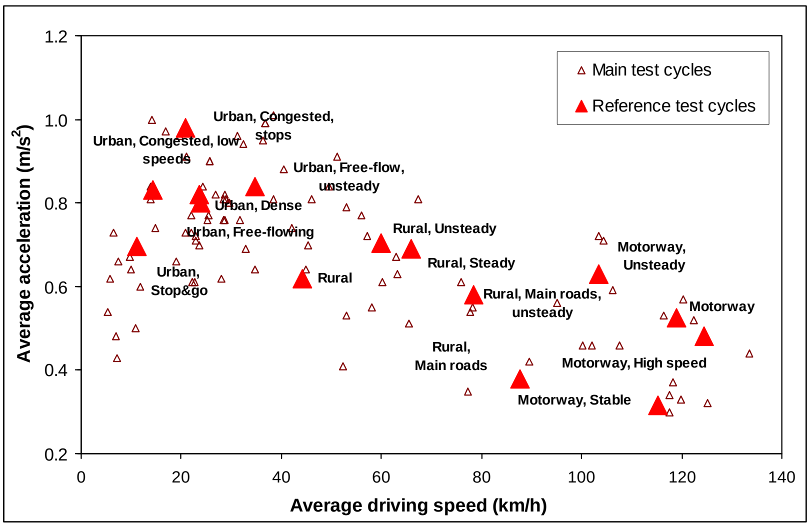

Figure 21: Characteristics of the main test cycles and reference test cycles representative of each class of the reference test patterns.

According to Joumard *et al.* (2006a), the process of classifying driving cycles and computing emission per reference cycle are important aspects of a robust modelling approach, and should be used as the basis for defining emission functions in relation to speed and cycle dynamics. For certain pollutants (NO_x and CO_2) and vehicle categories, the influence of cycle dynamics is illustrated in Figure 22.

Table 14: Classification of the cycles: definition and characteristics of the reference test patterns and reference test cycles RTC (in order of ascending average speed).

Reference test cycles (RTC)		Driving patterns	Avg. speed ($km\ h^{-1}$)	Avg. positive accel. ($m\ s^{-2}$)	Stop duration (%)	Stops per km
Urban	Stop&go	OSCAR.H1, OSCAR.H2, OSCAR.H3, TRL.WSL_CongestedTraffic	7	0.70	35	16.3
Urban	Congested, stops	ARTEMIS.urban_3	9	0.98	58	10.2
Urban	Congested, low speeds	ARTEMIS.urban_4	12	0.83	19	16.7
Urban	Dense	ARTEMIS.urban, ARTEMIS.urban_1	17	0.82	29	5.2
Urban	Free-flowing	ARTEMIS.urban_5	22	0.80	10	4.3
Urban	Free-flow, unsteady	ARTEMIS.urban_2	32	0.84	9	2.3
Rural		ARTEMIS.rural_3	43	0.62	3	0.5
Rural	Unsteady	ARTEMIS.rural, ARTEMIS.rural_1	58	0.71	3	0.3
Rural	Steady	ARTEMIS.rural_2	66	0.69	0	0.0
Rural	Main roads, unsteady	ARTEMIS.rural_4	79	0.58	0	0.0
Rural	Main roads	ARTEMIS.rural_5	88	0.38	0	0.0
Motorway	Unsteady	ARTEMIS.motorway_150_2	104	0.63	0	0.0
Motorway	Stable	EMPA.BAB, modemHyZem.motorway, TRL.MotorwayM113	115	0.32	0	0.0
Motorway		ARTEMIS.motorway_130, ARTEMIS.motorway_150_1	119	0.53	0	0.0
Motorway	High speed	ARTEMIS.motorway_150, ARTEMIS.motorway_150_3, ARTEMIS.motorway_150_4	125	0.48	0	0.0

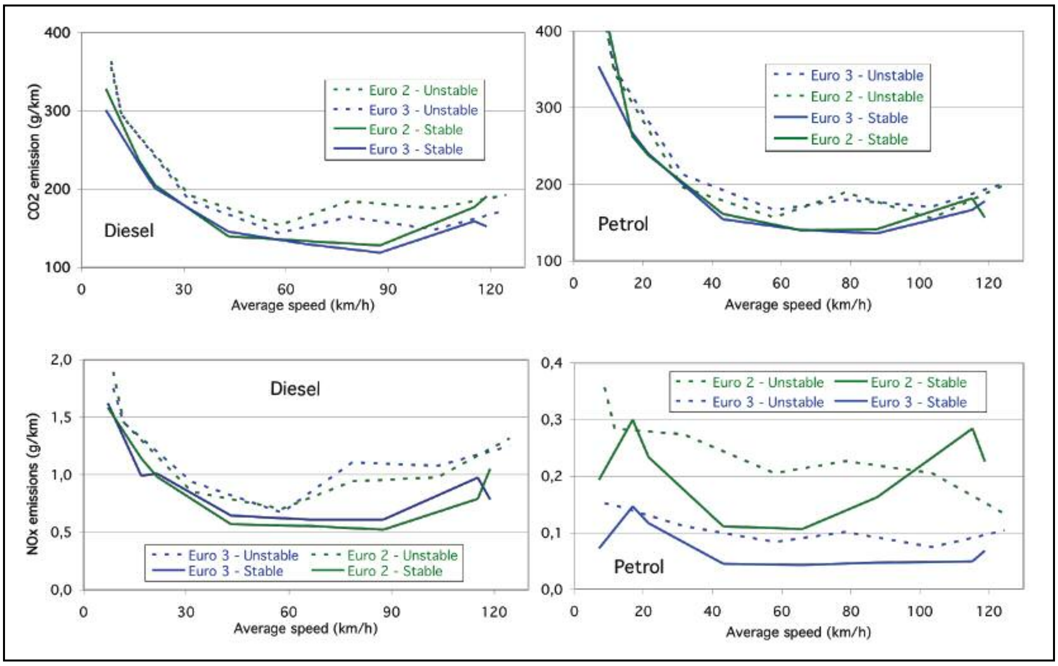

Figure 22: Dynamic influence on the CO_2 and NO_x emissions.

Gear-shift behaviour

The effects of five different gear-shift strategies on emissions were evaluated in ARTEMIS, and these strategies are briefly summarised in Table 15. The first two strategies were dependent upon the vehicle characteristics. The ‘cycle’ strategy was defined within the driving cycle, and was dependent upon the vehicle power-to-mass ratio. In the 'RPM' strategy the gear changes were defined for specific engine speeds. The ‘NEDC’ and ‘record’ strategies imposed gear changes which were independent of the vehicle characteristics. The ‘NEDC’ strategy imposed gear changes for given vehicle speeds, as defined in the NEDC itself. The ‘record’ strategy imposed the gear changes actually recorded on the road during the measurement of the corresponding driving patterns. In the ‘free’ strategy, gear changes were left to the discretion of the laboratory driver.

Table 15: Description of the five gear-shift strategies tested (André *et al*., 2003).

Strategy name	Description
‘Cycle’	Gear-shift pattern included in the design of the corresponding driving cycle (*e.g.* ARTEMIS).
‘RPM’	Gear-shift criteria defined in terms of given engine speeds.
‘NEDC’	Gear-shift criteria defined in terms of given vehicle speeds, as in the NEDC driving cycle.
‘Record’	Gear-shift pattern recorded on the road during data collection.
‘Free’	Gear shifts decided by the driver in the laboratory.

CO_2 was found to be the pollutant most sensitive to the gear-shift strategy, with a systematic emission variation between strategies of between 2% and 15**%**. CO and HC showed significant differences between some strategies, but NO_x emissions were not influenced. It was therefore considered possible to classify gear-shift strategies only according to their CO_2 emissions. For the ARTEMIS driving cycles the most polluting strategy was the fixed engine speed (RPM) one, whatever the situation, and the least polluting strategy appeared to be the fixed speed (NEDC) one.

Influence of the driver

During an emission test the driver attempts to reproduce the vehicle speed and gear-shift pattern defined in the driving cycle, but the reproduction is never perfect. The objective of this part of the work was to identify the influence of the driver on the accuracy of the emission factors, and to propose guidelines which minimised the associated errors. A review and statistical analysis of older data was initially undertaken (Schweizer, 1998). A total of fifteen driving cycles were then studied using a robot driver (Horiba ADS-1100) and four different human drivers. In order to compare the accuracy of the driving and the emissions obtained using the human drivers and the robot, four kinematic parameters were selected based on the difference between the reference speed and the actual speed (the ‘speed error’): the mean standard deviation of the speed error, the mean absolute speed error, the auto-correlation of the speed error, and the regression coefficient between the actual and reference speeds (Devaux and Weilenmann, 2002).

The robot showed a slightly better repeatability than the human drivers, but the difference was not significant. Some driving cycles were too ‘aggressive’ for the robot, which affected the repeatability. Except for CO_2, no significant difference was found between emissions over robot-driven or human-driven tests. The CO_2 emissions of the human drivers were, on average, 4% higher than for the robot. It was suggested that motions of the accelerator pedal with frequencies above 0.5 Hz, thus undetectable in the 1 Hz data set, may have been responsible. From these results, it was also concluded that the initial goal of separating the variance of the emissions caused by the driver from the variance of the car, test bench and analysers could not be achieved (Devaux and Weilenmann, 2002).

An assessment was also made of the various tolerance ranges and fail criteria applied by each participating laboratory to the reference driving cycle. The criteria for failure should be meaningful and achievable in practice for most tests. However, the tolerance ranges should not be too wide in order to avoid unnecessary emission variation. It was concluded that, in general, it is possible for a trained driver to follow a real-world cycle with tolerance of ± 2 km h^{-1} and ± 1 second, such that the tolerance limits are violated for less than 1% of the test duration. These tolerance ranges were recommended for wider use. A tolerance range of ± 1 km h^{-1}

and ± 1 second, on the other hand, leads to violation percentages of up to 50%. Higher violation percentages can arise under a number of conditions, such as when the car has insufficient power to follow the cycle, when wheel slip occurs, or when the car has a 'difficult' gearbox, resulting in slow gear changes.

3.3.4 Vehicle-related parameters

Technological characteristics

A total of 43 cars were tested at different laboratories over the NEDC and the three main ARTEMIS cycles in an attempt to identify potential variation in the response of different emission control technologies to cycles with different dynamics, engine speed levels and power demand. The cars differed in terms of their emission control technology, as described by Samaras *et al.* (2005b):

- *Petrol vehicles*: palladium three-way catalyst, formulation and loading of three-way catalyst, close-coupled three-way catalyst, catalyst physical design, exhaust gas recirculation, advanced engine management strategies such as rich start and secondary air injection, cold-start spark retard and enleanment, transient adaptive learning.
- *Diesel vehicles*: oxidation catalyst, exhaust gas recirculation, engine design, engine management.

As the dynamics, engine speed levels, power demand, and engine load patterns in the NEDC are quite different to those in the ARTEMIS cycles, the test programme should have identified any differences between the response characteristics of the various emission control technologies to cycles with different dynamics (Samaras *et al.*, 2005b). However, a basic statistical analysis showed only that the type approval level (Euro 2, 3 or 4) and the fuel type (petrol or diesel) had a significant influence on emission levels, and these parameters are already used for vehicle classification in emission models (Samaras *et al.*, 2005b). No correlations between emission behaviour and specific emission control technology were observed within the same type approval category. It is therefore unlikely that the introduction of detailed technological characteristics will improve the accuracy of emission factors for cars up to and including Euro 4. One obvious exception is the diesel particulate filter. This was not studied here, but can have a large effect on PM emission levels.

Emission stability

The short-term stability of emission measurements was examined at each laboratory involved in ARTEMIS. After a preconditioning with the NEDC, the ARTEMIS urban cycle was driven five times. Each ARTEMIS cycle was preceded by a 20-minute break so that the bag samples could be analysed and the dynamometer could be prepared for the next test. The second part of the test involved a similar sequence, but was performed using the ARTEMIS rural cycle. A total of 12 vehicles were tested, and short-term emission stability was assessed using the standard deviation and relative standard deviation of the measurements. Using these values, the measurement uncertainty could be divided into the uncertainty due to differences between vehicles (sample standard deviation) and the uncertainty due to a spread in test results for one vehicle (relative standard deviation) (Cornelis *et al*., 2005).

The results showed that the different standard deviations varied considerably according to the pollutant and the vehicle class. The relative standard deviation was lowest for CO_2 (variation of 1% over the five repetitions). The relative standard deviations for HC and CO were high for most cars (up to 71%), but the absolute standard deviation was small. NO_x emissions from diesel cars proved to be highly repeatable. The relative standard deviations for CO, HC and NO_x were similar for Euro 2 and Euro 3 petrol cars (Cornelis *et al*., 2005). The sample standard deviation was always much higher than the relative standard deviation. This indicated that the differences between the test results of several vehicles are larger than the differences one might expect when testing the same vehicle several times. The results indicate that for the derivation of emission factors using a large sample of vehicles and a small number of repetitions for each tests cycle is preferable to using a small vehicle sample with a high number of test repetitions.

Emission degradation

The effects of vehicle age, mileage and level of maintenance over long periods were studied via a review of the literature and the analysis of existing data. Two petrol vehicles were chosen for the measurements. The service interval defined by the manufacturer for both tested vehicles was 10,000 km, and the measurements were scheduled at mileage intervals of 20,000 km. Measurements were performed both before and after maintenance. The test protocol involved a cold-start NEDC, followed by a EUDC. After the analysis of the bag samples, two repetitions of the EUDC were executed in order to achieve engine warm-up, and the three ARTEMIS cycles were then performed (Geivanidis and Samaras, 2004). The correction factor approach to take into account the degradation of emissions with mileage was retained from the COPERT III model (Ntziachristos and Samaras, 2000a), and is given by the equation:

$$\boldsymbol{MC_{C,i} = a_M \times M_{mean} + b_M} \qquad \text{(Equation 1)}$$

where:

$\boldsymbol{MC_{C,i}}$	=	the mileage correction for a given mileage, pollutant ***i*** and a specific cycle
$\boldsymbol{a_M}$	=	the degradation of the emission performance per kilometre
$\boldsymbol{M_{mean}}$	=	the mean fleet mileage of vehicles for which correction is applied
$\boldsymbol{b_M}$	=	the emission level of a fleet of brand new vehicles

Brand new vehicles are expected to emit less than the sample average. It was assumed (arbitrarily, it appears, due to lack of data) that emissions do not further degrade above 120,000 km for Euro 1 and 2 vehicles, and above 160,000 km for Euro 3 and 4 vehicles. The effect of average speed on emission degradation was taken into account by combining the observed degradation lines over the two driving modes (urban and rural). It was assumed that for speeds outside the region defined by the average speeds of urban driving (19 km h^{-1}) and rural driving (63 km h^{-1}), the degradation was independent of speed. Linear interpolation between the two values provided the emission degradation in the intermediate speed region.

For Euro 1 and Euro 2 vehicles, the data from MEET could be used, as most of the ARTEMIS data for these vehicles originated from MEET. In order to estimate the degradation of Euro 3 and Euro 4 vehicles, the ARTEMIS data were used. Due to relatively small sample sizes, it was assumed that both Euro 3 and 4 vehicles would have the same degradation behaviour, and were not treated separately. Mileage effects were only examined for CO, HC and NO_x, as CO_2 emissions are unaffected by mileage (Samaras and Ntziachristos, 1998; Ntziachristos and Samaras, 2000b, 2001). The analysis was performed for two types of driving - urban and rural. The emissions of all vehicles were plotted against their mileage for three engine capacity ranges (<1.4 l, 1.4-2.0 l, and >2.0 l), and linear regression lines were fitted to the data. The conclusions of the work were as follows:

- For CO during urban driving, degradation in emissions was observed for each driving mode and for two engine capacity categories.
- For CO during rural driving, a degradation was observed for vehicles <1.4 l, while no degradation function was proposed for vehicles with engine capacity above 1.4 l.
- For HC a considerable degradation was observed only in the case of vehicles <1.4 l in urban driving mode.
- For NO_x a considerable degradation is observed only in the case of vehicles >1.4 l in urban driving mode.

Appropriate degradation functions are presented in Chapter 4. On average, the emissions of CO, HC and NO_x increased by a factor of 1.6 between 0 km and 100,000 km for Euro 1 and 2 petrol cars, by 14*%* for Euro 3 and 4 petrol cars. Emission degradation appears to be less important for recent vehicles. For example, NO_x emissions from Euro 3 and 4 petrol cars were not strongly affected by mileage. A series of measurements was also conducted on two specific vehicles in order to examine the influence of mileage and regular maintenance on emissions. No effect of maintenance was observed on the level of emissions, either as a consistent improvement following maintenance at the service intervals or as a function of mileage.

Fuel properties

The Auto/Oil and EPEFE programmes (hereafter referred to as EPEFE) provided linear equations to determine average exhaust emissions of the regulated pollutants from both petrol and diesel vehicles cars, according to fuel properties such as including density, aromatic content, olefin content, sulphur content and cetane number (ACEA and EUROPIA, 1996). In ARTEMIS, the EPEFE equations were used to predict which fuels would result in the minimum, maximum and average emission levels for petrol and diesel vehicles (Renault and Altran, 2002). Each participating laboratory was asked to sample local unleaded petrol and diesel fuel, and then each fuel was subjected to compositional analysis. Based on the compositional data and the EPEFE formulae, emissions over the NEDC cycle were assessed for each fuel. From the results, it was inferred that

NO_x was the pollutant most strongly influenced by petrol fuel quality, and therefore this pollutant was used as the criterion for determining which petrol fuels were to be tested. For the diesel fuels, PM was chosen as the criterion to select the fuels. Three petrol fuels (from Austria, France and Greece) and three diesel fuels (from Finland, Italy and France) were selected. In addition, two reference Euro 4 fuels were tested - one petrol fuel and one diesel fuel. Each fuel was tested with one vehicle, according to the following protocol: (i) a lubricant change in order to avoid any carry-over effect, (ii) a preconditioning phase: a cold EUDC (followed by a EUDC for diesel fuel), (iii) a cold-start NEDC, (iv) a cold-start ARTEMIS urban cycle and (v) the three hot-start ARTEMIS cycles. All the emission tests were performed twice. When replacing fuels the car was also driven for a distance of between 150 and 200 km to remove any carry-over effect from the previous fuel. The tests conditions complied with standard procedures. The exhaust gas temperatures upstream and downstream of the catalytic converter, and in the core, were also measured (Renault and Altran, 2002).

For the petrol fuels, the highest CO emissions were obtained using the Austrian fuel over the cold-start ARTEMIS urban cycle. The aromatic content of this fuel was the highest of those tested. For HC, the petrol composition should have a clear influence on emissions. For example, if the aromatic content of the petrol is high, the proportion of such compounds in the HC emissions ought to be high, and under cold-start conditions the temperature of the after-treatment system will not be sufficient to oxidise these heavy compounds. However, it was not possible to determine the precise influence of petrol composition on HC emissions, since emission levels were very low, particular over the ARTEMIS cycles. For NO_x, the influence of the aromatic content was similar that for CO and HC. For CO_2, no global trend or conclusions could be identified. Although the EPEFE equations have been confirmed in the laboratory for NO_x emissions, the situation is clearly different regarding CO and HC, and more important the ARTEMIS cycles. Indeed, the EPEFE formulae have been designed to evaluate emissions using the NEDC cycle, and not other driving cycles. The standard deviations over the ARTEMIS cycles were often too high to allow clear comparison. However, even though it was not possible to determine any real trend, or to explain the results, the fuel composition is a key consideration for the evaluation of NO_x emission factors. Indeed, for NO_x slight changes in the fuel composition (and physical characteristics) may affect the emissions. Furthermore, the Euro 4 petrol fuel always resulted in the lowest levels for each pollutant. Its chemical and physical characteristics are well defined, and within a narrower range, than the fuels allowed for Euro 3.

For the diesel fuels the results showed that over hot-start driving cycles CO emissions were very low and there were no significant differences between the fuels. Over cold-start cycles, on the other hand, significant differences between fuels were observed. These results could not be explained in terms of fuel effects. The results were similar for HC. For NO_x, no significant influence of fuel was observed. However, in the case of PM, significant differences were observed between the fuels (Figure 23), but the repeatability was sometimes very poor. For CO_2, the fuel composition had a marginal influence on emissions. Therefore, in spite of some significant fuel impacts, especially for PM, it was considered inappropriate to propose any correction for taking into account the fuel influence on emissions.

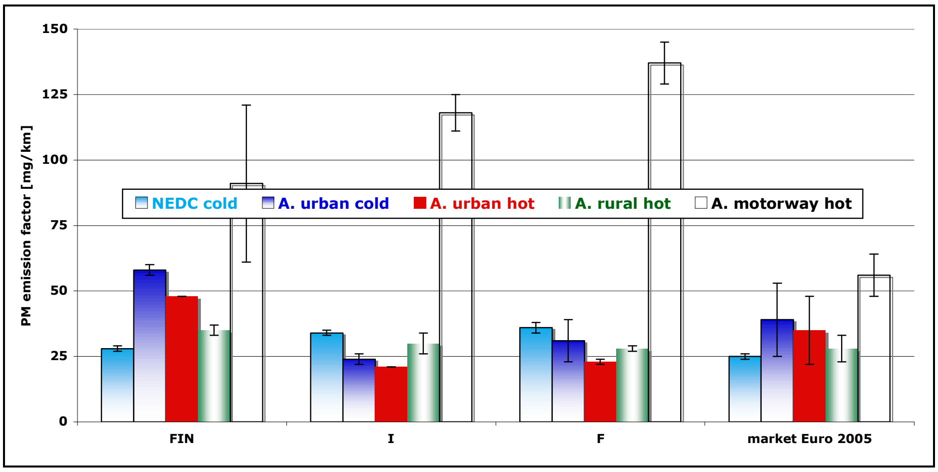

Figure 23: PM emission factors measured for one vehicle using four different fuels and five different driving cycles.

Cooling fan operation

The effects of various cooling fan parameters were investigated using six cars over the ARTEMIS urban and rural driving cycles. The parameters included fan type, height above the ground, the control of the air speed (with or without roller speed dependence), and the position of the engine bonnet (closed or open). The cooling fan arrangement was varied using a small blower, conforming with standard emissions test protocols, set at a distance of 30 cm from the front of the car, and used both in the normal position (directed towards the front of the vehicle) or directed below the engine. In addition, a large blower with a 1.5 m^2 cross-sectional area and regulated air speed was employed. This was used either with fixed air speeds (30 or 60 km h^{-1}, corresponding to 50% and 100% of the average speed of the cycle), or relative to the roller speed. In all tests the target ambient temperature was 23°C.

All the cars showed only small deviations (-3% to +2%) in CO_2 emissions, indicating a good basic level of reproducibility. However, the other exhaust components did not show any clear trends. The height of the small blower and the position of the bonnet had no significant effect on emissions. For petrol cars, a slight decrease in CO and NO_x emissions was generally noted when using the larger cooling fan and a higher air speed, compared with the normal fan, and a slight overall increase in HC emissions was observed with increased cooling air speed. In addition, the diesel cars tested seemed to be less sensitive to the cooling arrangement than the petrol cars. However, these trends were not consistent for all vehicles. Given the small number of cars tested, and the ambiguous nature of the results, it was concluded that correction factors for the effects of vehicle cooling fan arrangement could not be determined. However, a number of observations of the possible direction of the effects were noted, and these could serve as indicators in the overall evaluation of the sources of the disparity between the results obtained in different laboratories (Laurikko, 2005a).

Vehicle preconditioning

Vehicle preconditioning is required prior to emission tests in order to stabilise the thermal condition of the engine, exhaust after-treatment device, transmission, tyres and the dynamometer bearings. The effects of different preconditioning cycles were studied for five vehicles. The preconditioning cycles which were studied were 10 minutes of idling, 10 minutes at a constant speed of 80 km h^{-1}, the NEDC and the ARTEMIS urban driving cycle. The test protocol was as follows (i) a cold NEDC preconditioning cycle, (ii) a 10-minute delay with the engine switched off, (iii) the preconditioning test, and (iv) the measurement driving cycle, performed four times. The measurements were conducted at an ambient temperature of between 20°C and 25ºC, and local, commercial grade fuels were used (Olàh, 2005).

The results showed that preconditioning using the 10-minute idling cycle resulted in the largest emission values over all measurement cycles (Olàh, 2005). Emissions over the ARTEMIS rural cycle were influenced to a lesser degree by preconditioning than emissions over the ARTEMIS urban cycle. The emissions of diesel cars were influenced to a lesser degree by preconditioning than those of petrol vehicles. Emissions over the ARTEMIS urban cycle were most strongly influenced when the same cycle was used for preconditioning. The EUDC cycle as measurement cycle was influenced less by preconditioning than the other cycles (the first part of the NEDC cycle can be considered as a kind of preconditioning in itself). The method of preconditioning had no significant influence on emissions from modern closed-loop-controlled vehicles with a catalyst.

The main conclusion of the work was that the 10-minute cycle at a constant speed of 80 km h^{-1} was the most suitable preconditioning cycle, as it resulted in the lowest emission levels and the lowest standard deviation for the majority of the measurements. Such a cycle is simple to conduct and is reproducible. The length of the preconditioning can be modified without changing the cycle characteristics. The average engine load, engine temperature and tyre temperature can be modified and adjusted by changing the constant speed level.

3.3.5 Vehicle sampling method

Method of vehicle sampling

The vehicle sampling methods used by the ARTEMIS laboratories included different types of random selection from car rental companies, private owners or car manufacturers. A survey was conducted to identify the terms used by the laboratories to characterise their sampling methods, to describe the methods used for obtaining vehicles (André, 2002). The surveys revealed that the average number of vehicles per measurement campaign was between 10 and 25. The choice of the number of vehicles was determined principally from a financial perspective (cost of instrumentation, workforce, rent of vehicles, *etc.*). Other criteria included the representativeness of the sample, which was often determined using national or European statistics (*e.g.* sales, fleet composition, traffic), and the availability of the chassis dynamometer. The minimum number of vehicles below which laboratories did not analyse the results (or did not have confidence in their representativeness) was usually between three and ten. The representativeness of the sample was assessed according to several parameters, including (broadly in decreasing order of importance) fuel type, emission standard, engine technology, engine capacity, age, mileage and vehicle model. Some laboratories used statistical databases for assessing the representativeness of their sample according to these characteristics. The main sources of test vehicles were rental agencies, garages, dealerships or companies. Otherwise, vehicles can be selected from a list of private owners. In such cases, the owners are usually entitled to a financial incentive and a rental vehicle during the test period. Some laboratories pre-test vehicles, whereas others do not, but all the laboratories reject vehicles having serious defects.

Vehicle sample size

The influence of the sample size on the average emissions for the different vehicle types was studied via a statistical investigation of existing data. The main outcome was the development of guidelines to determine the minimum vehicle sample sizes for ensuring the highest possible accuracy of emission factors. The study was based on the Inspection Maintenance measurement campaigns of 1994 (Samaras *et al.*, 2001), and the HyZem campaigns of 1997 (Joumard *et al*., 2000). The selected samples were representative of the French vehicle fleet, and were split into three vehicle categories: non-catalyst petrol, catalyst petrol, and non catalyst diesel. It was found that the minimum number of vehicles to obtain a representative emission factor or model for a given vehicle category at the highest level of detail (*e.g.* Euro 3 petrol cars, <1400 cc) usually exceeded 10 (Lacour and Joumard, 2001).

3.3.6 Laboratory-related parameters

Ambient temperature

Ambient temperature influences both cold-start and hot-start emissions, but the effects have rarely been studied over real-world driving cycles. In total, 31 passenger cars were tested over the ARTEMIS driving cycles. Firstly, a cold-start test was performed, and when the engine was fully warmed-up a hot-start test was performed. The ambient temperatures examined were -20^{o}C, -7^{o}C and 23°C. The tests were conducted at two separate laboratories: VTT and EMPA. At VTT, single batches of petrol and diesel fuels were used. The petrol fuel was unleaded (RON95) and the diesel fuel had a maximum sulphur content of 10 ppm. At EMPA two types of petrol and one type of diesel were used. The first petrol fuel was unleaded (RON 98), and contained 0.6% (vol) benzene and 27.5% (vol) aromatics, whereas the second petrol fuel was unleaded (RON 95) and contained 3.0% (vol) benzene, 39.4% (vol) aromatics. The diesel fuel had 18.8% (mass) mono-aromatics, 3.3% (mass) bi-aromatics and 0.5% (mass) tri-aromatics (Laurikko, 2005b).

The results showed that emissions of CO, HC, NO_x and CO_2 generally increased at lower ambient temperatures. However, in some cases a decrease in CO was detected, most notably in the case of petrol-fuelled cars during rural and motorway driving. On average over all tested driving cycles the ratios between emissions at -10°C and emissions at 20°C (based on a regression model) for all tested petrol-fuelled cars (Euro 2, Euro 3 and Euro 4) were 0.96, 1.54, 1.11 and 1.05 for CO, HC, NO_x and CO_2 respectively, and for diesel Euro 2 cars the equivalent ratios were 2.14, 1.73, 1.04 and 1.04 (and 1.0 for PM). In general, the ratio was independent of the emission standard of the vehicle. However, for urban driving (*i.e.* low speed and low engine load) HC emissions showed an increasing sensitivity to low ambient temperature with an advance in Euro standard (*i.e.* Euro 4 cars were the most sensitive, and the pre-Euro 1 cars were the least affected). The influence of ambient temperature on emissions was generally linear, but in a few cases (urban HC for petrol Euro 4, and motorway HC for diesel Euro 2) an exponential function gave better results (Laurikko, 2005b).

Ambient humidity

The effect of ambient humidity on NO_x emissions is recognised, and a correction function is applied to all type approval measurements. However, the effect has only been studied for older types of vehicle. It was therefore necessary to update the NO_x correction function for modern vehicles, and to examine the effects on other pollutants. Emission tests were performed on eleven vehicles using a cell equipped with a humidification system to keep the humidity level within a specified range. In order to assess humidity levels outside the range deemed acceptable in type approval (5.5 to 12.2 g/H_2O per kg of dry air) the tests were conducted in winter when the ambient air was very dry. Additional water vapour was then added to the air to reach 'normal' and 'above-normal' conditions (Laurikko, 2005c).

Some typical results for NO_x are given in Figure 24. The results are grouped for Euro 2 and Euro 3 petrol cars, and for diesel vehicles including both Euro levels. Both the individual test results and the arithmetic mean values are plotted for each group under 'low', 'medium' and 'high' humidity conditions, and linear regression functions are fitted to the data. The results showed that an increase in ambient humidity lowered the NO_x emissions, which was the general trend expected from the humidity correction used in legislative testing. Over the urban test cycle the standard correction was nearly valid for diesel cars, with less than a 5% deviation. However, both groups of petrol cars would need much stronger corrections, as the relative change over the allowed humidity range was about 35% for the Euro 2 vehicles and over 55% for the Euro 3 vehicles. The normative factor only corrects emissions by around 20% over the same range of humidity. Therefore, the standard correction factor is too small. However, in the case of rural driving all the linear correction models developed in ARTEMIS were very similar, and the resulting correction was even lower than that provided by the standard method. Hence, using the standard correction factor for rural cycles actually leads to a slight 'overcorrection'. It should be noted that the standard deviation of all the pooled results for the urban cycle was two to three times higher than that for the results from the rural cycle. Therefore, the validity of the analysis is greater for the rural case (Laurikko, 2005c).

There was hardly any correlation between ambient humidity and emissions for petrol CO and petrol Euro 2 HC (correlation coefficients less than 0.2). In case of diesel vehicles, the correlation coefficients between CO emissions and humidity were 0.60 (rural) and 0.73 (urban). For HC, the corresponding values were 0.28 (urban) and 0.41 (rural). There was a clear influence of humidity on CO emissions from diesel cars and Euro 2 petrol cars during urban driving, and on HC emissions from diesel cars, petrol Euro 2 cars or petrol Euro 3 cars during urban driving.

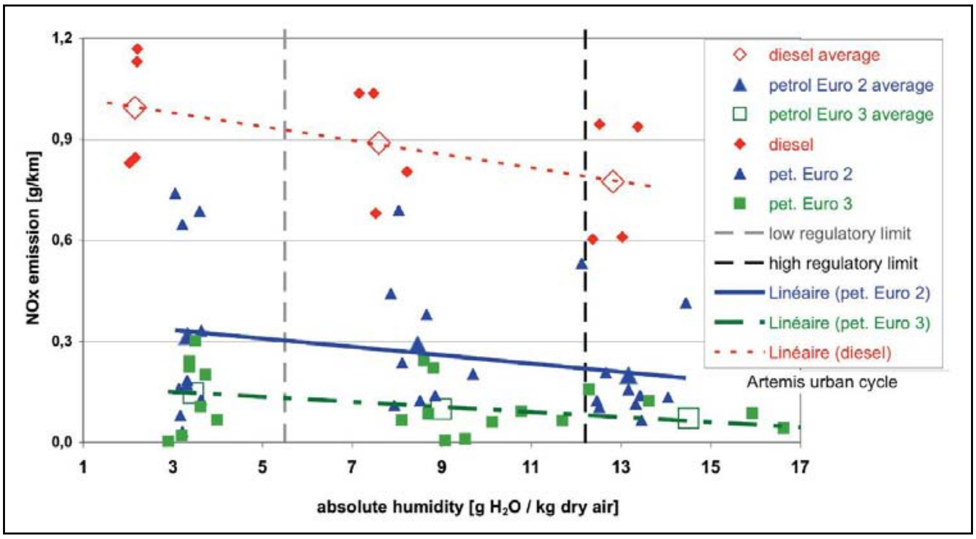

Figure 24: NO_x emissions over the ARTEMIS urban driving cycle as a function of ambient humidity. The lower and higher regulatory limits of humidity are also shown (*e.g.* EU directive 70/220/EEC).

Dynamometer settings

Emissions and fuel consumption are strongly dependent upon engine load. Hence, discrepancies in dynamometer load settings might have a significant effect on emission and fuel consumption measurements. A questionnaire was sent to the laboratories participating in ARTEMIS in order to obtain information on the methods used to define chassis dynamometer settings. It was assumed that the ARTEMIS laboratories were representative of other laboratories.

A vehicle's road load is usually expressed as a second degree polynomial:

$$\textbf{Road load power} = A \times v^2 + B \times v + C \qquad \text{(Equation 2)}$$

Where:

- A = the coefficient for driving resistance, dependent on the square of the speed
- B = the coefficient for driving resistance, linearly dependent on speed
- C = the coefficient for driving resistance, independent of speed
- v = the speed

The coast-down method is commonly used to define the road load of a vehicle, and the procedure is described in Directive 70/220/EEC. The method is based on the equilibrium of vehicle inertia with vehicle drag and rolling resistance during deceleration, with the gear positioned in neutral. The reference mass is determined either by weighing or by using information from vehicle registration documents. Alternatively, look-up tables are provided in Directive 70/220/EEC, in which the coefficients A and C are presented for different reference mass classes. Most of the ARTEMIS laboratories either used road load information derived from coast-down tests or the look-up tables in the Directive.

Two extreme chassis dynamometer settings (minimum and maximum) and one average setting for static road load and vehicle inertia were defined (Vermeulen, 2005). It was assumed that the polynomial approach of the road load determined from a coast-down procedure gave the best approximation of the 'true' (average) road load. Potential errors during testing (*e.g.* reference mass, speed, dynamometer load) were used to determine the minimum and maximum road loads. The error on the chassis dynamometer load was taken to be ±5%. The three sets of settings were used to perform emission tests on five vehicles using the cold-start NEDC and the three hot-start ARTEMIS driving cycles (Vermeulen, 2005).

There was found to be a statistically significant effect of the dynamometer settings on CO_2 emissions and fuel consumption for both petrol and diesel cars. CO_2 and fuel consumption increased with an increase in road load. Deviations of -12% to -4% were observed for the results of the minimum settings compared with the average settings. Deviations of +2% to +25% were observed for the results of the maximum settings compared with the average settings. The effect varied with the driving cycle.

Higher loads may cause higher drive line efficiency, but the cycle characteristics determine the share of static and dynamic situations during the driving cycle. Because the relationship between the chassis dynamometer settings over different driving cycles and FC (or CO_2) is not proportional, the results should be used to define a range of uncertainty caused by worst case chassis dynamometer settings. For the regulated components CO, HC and PM, no statistically significant influences were observed for petrol and diesel vehicles. NO_x emissions from petrol vehicles were also unaffected. However, a clear positive correlation was observed between NO_x emissions from diesel cars and the road load setting. This was according to expectations, as diesel engines commonly produce more NO_x when they operate at higher engine loads. In the case of CO emissions from petrol vehicles, an increase was observed over the ARTEMIS rural and motorway cycles using high road load settings, but again this effect was not significant. From the theory, however, it would be expected that CO and HC emissions increase at very high engine loads. From the results of this investigation there were no clear indications that altered chassis dynamometer settings explicitly influenced emissions of CO, HC, NO_x or PM. The very small size of the vehicle samples (three petrol cars and two diesel cars) did not permit a clearer conclusion. It was found that chassis dynamometer settings may vary depending on the method chosen to determine the settings, the accuracy of the method and the variation of ambient conditions. Because the effects of altered settings on CO_2 (and fuel consumption) are significant, it is recommended that the methods used to determine the chassis dynamometer settings should be investigated for systematic errors (Vermeulen, 2005).

Dilution ratio

The dilution of the exhaust gases by non-polluted air forms the basis of the constant volume sampler (CVS). The dilution ratio varies according to the exhaust flow, but must remain within a limited range. The effects of changes in the dilution ratio were investigated for a total of eight diesel and petrol vehicles. Between two and five different dilution ratios were tested per vehicle. When the results were presented as a percentage deviation from the reference value - the emission value for the dilution ratio that would be normally selected for the respective measurement – no systematic trends were observed. The only notable exceptions were diesel PM emissions, for which there was a tendency towards higher emissions with an increase in the dilution ratio, and HC, for which the trend was in the opposite direction. The decrease in HC emissions may be attributed to the higher condensation of particles which is measured as an increase in PM emissions (Geivanidis *et al*., 2004).

Sample line temperature

For diesel vehicles the exhaust sample line must be heated to 190°C, according to the standard procedure, in order to avoid liquefaction of some hydrocarbons. The effects of a lower sample line temperature (160^{o}C) were investigated. The lower temperature resulted in higher HC emission values, but this observation was contrary to expectations, as the point of heating to the higher temperature is to increase the fraction of HC retained in sample (Geivanidis *et al*., 2004).

PM filter preconditioning

A diesel passenger car was tested using PM filters preconditioned at different temperatures and humidity levels. The procedure consisted of reference tests with conditioning and weighing of the particle filters at an average temperature and humidity in a conditioning room, and emission tests were conducted using the defined minimum and maximum values for these conditions. The minimum and maximum values were defined by the capability of the climate control system to adjust to a certain range of temperature and humidity. No effects of filter preconditioning were observed, and all variations were within the repeatability ranges (Geivanidis *et al*., 2004).

Response time

The delay of emission measurements caused by the CVS system and the analysers is crucial for instantaneous measurements and second-by-second emission modelling, but also for standard HC measurements on diesel engines. As delay times may vary due to different concentrations, temperatures and pressures, the gas flow through the CVS system was modelled to find a correction function of the recorded emissions.

There are several potential systematic problems associated with instantaneous emission measurement. The emissions recorded at the analysers are delayed and smoothed compared with the emission events at the location of formation due to (i) the transport of the exhaust gas to the analysers, (ii) the mixing of exhaust gas especially in the silencer and the CVS tunnel and (iii) the response time of the analysers. The transport time of the exhaust gas to the analyser is determined by the air flow velocity in the exhaust system of the vehicle and the CVS tunnel, and in the related connection pipes. The velocity of the undiluted exhaust gas is highly variable over time, since it depends on the exhaust gas volume flow. The volume flow mainly depends on the engine speed and engine load. When combined, the varying transport times and the analyser response times can shift the signal by around 1-10 seconds (depending on the engine, the exhaust system, the CVS system, the analyser used and the engine load). Mixing effects during the gas transport and the analyser response behaviour also add a smoothing effect on the signals. These inaccuracies are usually compensated over the complete test cycle, such that the integral of the instantaneous measurement agrees with the bag value. However, in most instantaneous emission models the mapping of emissions is performed by statically relating the emission signals to causative variables such as vehicle speed, vehicle acceleration and engine speed. As a result of this static approach, the emission values can be correlated to the correct engine state of the car only if they are at the correct location on the time scale. Thus, instantaneous models are heavily affected by inaccurate time alignments.

It was noted by Weilenmann *et al*. (2003) that modern petrol cars with three-way catalysts and lambda control emit most of their pollutants during transient emission peaks. These peaks typically last between 0.5 seconds and 1 second, and show a frequency content of about 3–5 Hz. A significant part of the detail of the signals is therefore lost at the usual sampling rate of 1 Hz. The authors recommend a sampling frequency of 10 Hz.

In order to minimise the errors resulting from inaccurate time alignments, EMPA and TUG developed methods to compensate for the delay and smoothing of instantaneous emission measurements. Specially calibrated for the respective chassis dynamometers, both methods are designed to explain the change in the emission value from their location of formation to the analyser signal by formulae, and to invert these formulae to produce equations which transform the analyser signal into the engine out (or catalyst-out) emission value (Le Anh *et al.*, 2005). The main difference between the TUG and EMPA models is that the EMPA model is more detailed but needs modal measured data on the exhaust gas volume flow and information on the volume of the exhaust gas system of the tested cars. The TUG model has a simpler approach. However, both methods improve the quality of instantaneous emission signals significantly (Zallinger *et al*., 2005; Joumard *et al*., 2006b).

As an example, Figure 25 shows the oxygen signal at the catalyst outlet after it has been reconstructed from the analyser signal. The thick blue line is the signal measured by a fast oxygen analyser *in situ* at the catalyst-out location. The thin red line is measured by a standard oxygen analyser attached to a raw gas line, about 10 m long, connected to the tailpipe of the car. The dotted green line is the signal which has been reconstructed from the red signal by compensating for the transport dynamics of the sampling line. The dashed black line is reconstructed from the green line, compensating for the time-varying transport in the car exhaust system.

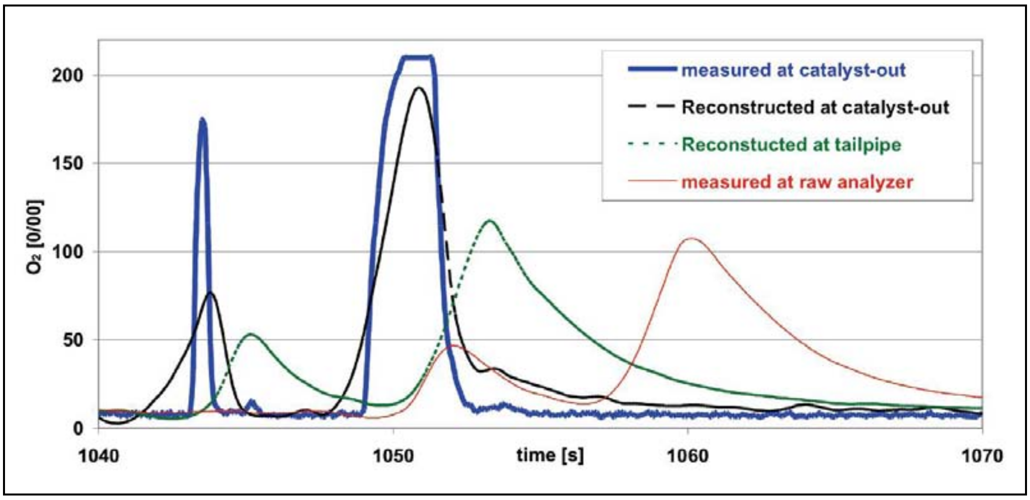

Figure 25: Overall inversion of the instantaneous concentration measured by gas analyser, using the EMPA model.

Using signals from the diluted measurements, the quality of the reconstructed signals showed a maximum time error of 2.5 seconds, which is significantly better than using the original signal, which had a time error of up to 25 seconds, but which is notably worse than using the raw line. From Figure 25 it is clear that using uncorrected signals from modal measurements leads to huge errors in the allocation of emissions to the corresponding engine operation conditions. Since the transport time of the undiluted part of the sample system depends on the exhaust gas volume flow, and thus on the engine load conditions, the misalignment between engine load and emission signal is highly variable over a test cycle. Thus, the constant time shift of measured signals used in previous models does not lead to a satisfactory result but to distorted vehicle emission maps.

Dilution air conditions

Measurements with ambient dilution air were compared with measurements using two different levels of 'polluted' dilution air: a 'low' level and a 'maximum' level. The values considered as standard (0.4 ppm CO, 3-4 ppm HC, 0.1-0.2 ppm NO_x) were common to the participating laboratories. The low level of polluted dilution air (2-3 ppm CO, 11-12 ppm HC, 1-1.2 ppm NO_x) was representative of the highest concentrations measured in the ARTEMIS laboratories. The high level of polluted dilution air represented improbable conditions (11-12 ppm CO, 20-21 ppm HC, 5.5-6 ppm NO_x), which could only been reached because of an incident such as a gas or fuel leak. In both cases, the dilution air pollution was obtained by injecting a specific quantity of CO, HC and NO_x upstream of the dilution tunnel. For each of the three pollution levels, two repetitions of each cycle were performed. Two vehicles were tested over cold-start and hot-start driving cycles, but with the three levels of polluted dilution air. The significance of the differences between the results obtained using the three dilution air pollution levels was investigated using a one-way analysis of variance for CO, HC and NO_x emissions. The results showed that for the level of pollution in the dilution air had no statistically significant effect on the emission factors (with the exception of HC for one car during the ARTEMIS urban cycle) (Prati and Costagliola, 2004). However, the work did not include particle number measurements. The conditions of the dilution air (dilution ratio, temperature) do have a significant influence on particle number measurements.

3.3.7 Round robin tests

In the ARTEMIS round robin, a single vehicle (a Euro 3 petrol car) was tested successively in the nine participating laboratories. The test schedule is shown in Table 16. The exercise lasted almost 8 months. The vehicle started the tour with a full fuel load, and that fuel was continuously used in the successive tests until the level became low, and then the vehicle was refuelled with the normal commercial fuel available at that laboratory.

The testing protocol determined the vehicle road load settings for the dynamometer using either the coefficients of the basic road-load formula or the coast-down times (*i.e.* the time intervals between two pre-determined speeds on a free-rolling coast-down on the chassis dynamometer. As a further reference, the net power absorption at two speeds was also included. The test sequence was: (i) a cold NEDC, (ii) a hot NEDC, (iii) a hot ARTEMIS urban and (iv) a hot ARTEMIS rural (*i.e.* 6 bag samples in total), under normal ambient temperature conditions. At INRETS this complete protocol was executed ten times at the start of the round robin to look at the stability of the vehicle emissions, between two and four times for the subsequent eight laboratories, and finally five times at INRETS at the end of the round robin. Apart from the temperature, humidity and barometric pressure, data were also collected to improve the analysis and assessment of the spread among the testing conditions. The vehicle exhaust emission test was augmented with stand-alone standard gas concentration measurements using a set of calibration gas samples which travelled with the vehicle. The results of the analyses of these gas samples were also collected as part of the test programme. This made it possible to investigate the accuracy of the emission analyser benches as well as the overall test facility, including the set-up and conduct of the full protocol.

Table 16: Laboratory order, timing and fuels used during the round-robin exercise. The numbers of tests over the full protocol are also shown.

Laboratory	Location	Country	Test period	Fuel	Number of tests
INRETS	Bron	F	27-07-2004 to 07-09-2004	Unleaded 95 RON	10
IM-CNR	Napoli	I	02-11-2004 to 04-11-2004	Unleaded 95 RON	3
TUG	Graz	A	16-11-2004 to 18-11-2004	Unleaded 95 RON	2
KTI	Budapest	H	02-12-2004 to 07-12-2004	Unleaded 95 RON	2
EMPA	Duebendorf	CH	13-12-2004 to 20-12-2004	Unleaded 95 RON (Migrol)	4
TNO	Delft	NL	28-12-2004 to 29-12-2004	RON 95, S<50ppm	2
MTC	Haninge	S	18-01-2005 to 19-01-2005	Blend 95, RVP 63	2
VTT	Espoo	FIN	27-01-2005 to 28-01-2005	Blend 95, RVP 63	2
LAT	Thessaloniki	GR	18-02-2005 to 24-02.2005	Unleaded 95 RON	3
INRETS	Bron	F	07-03-2005 to 11-03-2005	Unleaded 95 RON	5

The results showed that assessing the variation between the results obtained in different laboratories is not an easy task, and quite a large spread in the results was recorded (Laurikko, 2005d). Two of the most influential factors were probably non-uniform fuel and variations in ambient test cell temperature. However, the emission behaviour of the car appeared not to be very stable, with poor repeatability. Therefore, part of the spread of results encountered in this exercise was probably a result of this vehicle variation, and not just from the differences between laboratories.

The best accuracy (lowest spread in the results) was encountered for CO_2, for which the overall average deviation at each laboratory ranged between +7% and -10%, with an average coefficient of variation of around 5%. The next best was CO, for which the average spread ranged between +30% and -50%, and the average coefficient of variation was around 40%. For NO_x the figures were somewhat larger, between +60% and -35%, and an average coefficient of variation below 40%. The highest spread by far was recorded for HC, for which the average deviation was between +120% and -50% compared with the average result of the whole group, and the average coefficient of variation was around 60%. When comparing these variations to those values calculated on the basis of the repeated tests at INRETS (Figure 26), it can be concluded that the overall variability recorded for CO in the round robin test was roughly of the same order of magnitude as the ‘basic’ repeatability combining the repeatability of the laboratory and fluctuations in the car performance. However, with HC the overall spread in the results over the whole round robin test was higher, suggesting that external factors such as the change in fuel quality affected and lowered the repeatability. For NO_x, the overall round robin test variability was also somewhat higher than the basic value obtained from one laboratory alone, but the reasons for this are not known.

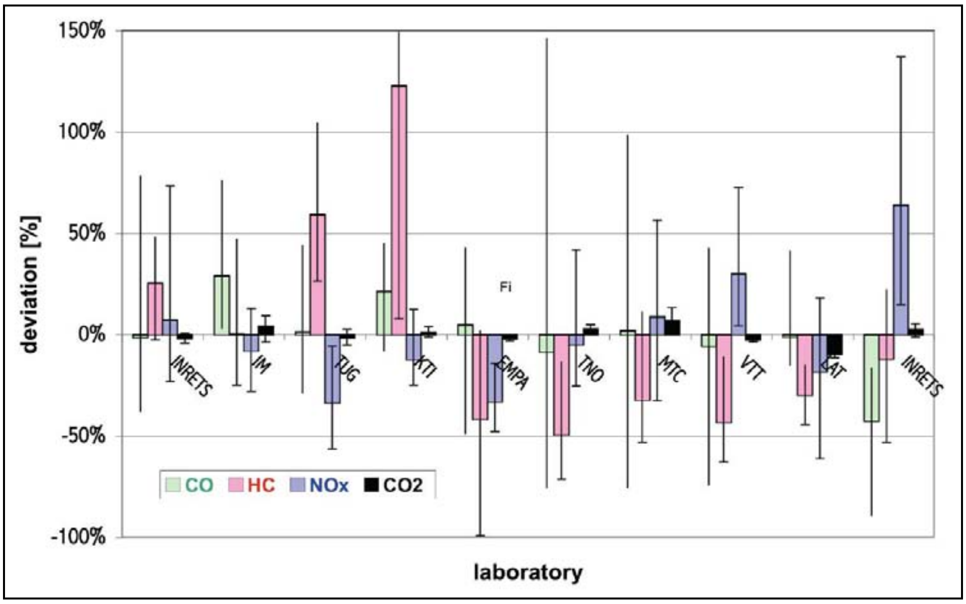

Figure 26: Relative emission deviation for each laboratory, in comparison with the average all laboratories considered (average for all cycles together for each component), as measured during the round robin test, with high-low bars marking the largest deviations.

A closer assessment of the data revealed that it was not possible to develop any ‘correction factor’ or ‘lab factor’ which could be applied to the full database of results collected in ARTEMIS. This conclusion was mainly based on two factors. The first of these factors was the quite long temporal span (over one year) between the round-robin exercise and the initial testing phase, during which time some the measurement equipment had been upgraded, and in one case the entire facility upgraded (the CVS, analysers and chassis dynamometer were renewed at TUG). Therefore, it was probable that the results measured in this round robin exercise were different from those that would have been obtained if the round robin test had been executed parallel to the actual testing itself (this was not possible for a number of reasons). Secondly, when different driving cycles were used the spread of results became random, and none of the laboratories showed consistently higher or lower results compared with the average. Instead, laboratories could show results higher-than-average in one test case (driving cycle or pollutant), and vice versa when another driving cycle or pollutant was considered. Only if each of the pollutants was considered separately could a few cases be found in which the results of a laboratory over all cycles tested could be consistently higher or lower than the average. This can be seen in Figure 26, which shows the emission variation (all cycles) for each laboratory. Even in those laboratories which appear, overall, to lay above or below the average of the group, high or low bar ends extend to the other side of the y-axis, indicating that the overestimation (or underestimation) was not consistent.

3.4 Effects of different test parameters: heavy-duty vehicles

3.4.1 Background

The information in this Section of the Report is derived from the ARTEMIS work on HDVs (Rexeis *et al*., 2005). The main aims of the work were:

(i) *To collect a large amount of HDV emission data from a range of European sources.* Emission measurements for 102 heavy-duty engines were obtained from ARTEMIS and other national and international programmes, culminating in the most extensive database on HDV emissions in Europe.

(ii) *To develop a model capable of accurately simulating emission factors for all types of HDV over any driving cycle and for various vehicle loads and gradients.* The resulting tool – PHEM (Passenger car and Heavy-duty Emission Model) - estimates fuel consumption and emissions (CO, THC, NO_x and PM) based on the instantaneous engine power demand and engine speed during a driving cycle specified by the user. The model combines steady-state engine maps with correction functions for transient operation.

(iii) *To acquire the necessary model input data*. Representative driving cycles were developed as model inputs. These were obtained through a review of the literature, an extensive analysis of all available on-board measurement data from driving behaviour studies, and a tailored measurement programme.

(iv) *To generate a database of emission factors for the ARTEMIS inventory model.* An emission factor and fuel consumption database for conventional HDVs was compiled using PHEM, based upon typical vehicle data, engine data and representative driving cycles. Emission factors were produced for almost 170,000 combinations of pollutant, vehicle category, Euro class, driving cycle, vehicle load and road gradient. The effects of fuel quality, level of vehicle maintenance and various other factors were also investigated in detail.

Although HDVs were studied in great detail in ARTEMIS, the investigation of emission test parameters was less extensive than that for cars, and there was no round-robin programme. Nevertheless, information was obtained on a number of different parameters which are important for emission factor development, and this information is summarised below.

3.4.2 Emission-control technology

The newest vehicles tested in ARTEMIS were compliant with the Euro III emission standard. In order to achieve the Euro IV and Euro V limits PM emissions will have to be reduced by approximately 70% to 90% compared with Euro III. The reductions in NO_x emissions to reach Euro V range from 50% to nearly 70%. The technologies required to achieve such reductions will make the overall system much more complex.

The assessment of the emission behaviour of engines meeting the Euro IV and Euro V standards was highly uncertain, as no production vehicles were available for measurement. Furthermore, the effects of new technologies (*e.g.* SCR, particle oxidation catalysts) were difficult to predict. It was concluded from the measurement programme on Euro II and Euro III engines that simply extrapolating emission factors from older engine technologies to future standards according to the future emission limits is not a suitable approach.

Compared with Euro III diesel engines, Euro IV and Euro V engines must also comply with the emission limits during the ETC. Consequently, optimisation at the single test points of the ESC will not be sufficient to meet the emission limits at type approval. With this regulation it can be assumed that emission levels during real-world driving conditions may decrease more compared with Euro III than the reduction in the emission limit suggests. However, most of the ETC is located in the same region of the engine map as the ESC. Thus, it will not be absolutely necessary for a manufacturer to optimise the emission levels over the complete engine map in order to meet the emission limits.

In general, three approaches for meeting the Euro IV and Euro V type approval limits will be available in the near future: improved engine technology, exhaust gas after-treatment and alternative combustion concepts. Whilst compliance with the Euro IV limits could be achieved with improved conventional engine technologies (fuel injection, exhaust gas recirculation, variable turbine geometry at the turbo charger, *etc.*), this is rather unlikely for Euro V. For example, the engine efficiency would be unacceptable for reaching the 2 g/kWh NO_x. Using exhaust gas after-treatment systems could reduce NO_x and PM to the targeted levels, but the problems with these systems are their unproven durability and the additional investment costs. Potential technologies for Euro IV and Euro V engines are briefly discussed below

PM-reduction technologies

Various filter-based after-treatment systems are currently being developed to reduce PM emissions from HDVs – these are collectively known as diesel particulate filters (DPFs). For all these systems, the main technological challenges are controlled regeneration of the filter and durability. Particulate filters also have additional investment costs, and result in a slight penalty in terms of fuel efficiency (1-3%). Therefore, research is under way to improve engine technology so that PM limit values can be met without the use of filters. The systems described below are examples of current developments.

- *Continuously-regenerating trap (CRT™, Johnson Matthey).* This technology uses the NO_x in the exhaust gas to continuously regenerate the trap. An oxidation catalyst is placed upstream of the filter to convert NO to NO_2. This process requires temperatures above 230°C to start the filter regeneration, and 350°C to achieve equilibrium. Additional systems for active regeneration may be needed, such as electrical or fuel burner heaters, potentially supported by a fuel additive.

- *Fuel-borne catalysed filter.* In this system, an additive is used to reduce the soot ignition temperature. The additive is introduced into the fuel tank after refuelling. The additives currently used are cerium, iron and strontium. The main disadvantage of this approach is the need for an additional tank for the additive.
- *Diesel particulate catalyst.* Besides filter-based systems, in which the exhaust gas flows through a porous medium, 'open' systems have recently been developed. Due to the special shaping of the catalyst, the exhaust gas flows into a storage medium where particles are deposited. If the storage medium is full, the exhaust flows through the open channels of the catalyst without further separation of the particles. As soon as the catalyst reaches the regeneration temperature, the particles are burnt off and the system can work at the original efficiency level.

NO_x-reduction technologies

There are currently two main approaches for reducing NO_x emissions: selective catalytic reduction (SCR), and exhaust gas re-circulation (EGR). In the SCR system, urea is dissolved in water and is injected into the exhaust gas stream, where a hydrolysis process converts it into CO_2 and NH_3. Alternatively, the NH_3 can be produced from ammonium carbonate. The ammonia is used as a NO_x-reducing agent, producing nitrogen and water in the catalyst. To prevent ammonia from passing into atmosphere (ammonia slip) an oxidation catalyst is usually fitted downstream of the SCR catalyst. EGR is used to reduce NO_x emissions by recirculating a portion of the exhaust gas back into the combustion chamber. This reduces the oxygen available for combustion, and leads to lower peak temperatures, thus inhibiting the formation of NO_x. There are different principles of exhaust gas recirculation: (i) external high-pressure EGR, (ii) external low-pressure EGR and (iii) internal EGR. All of these options may be used in Euro IV and/or Euro V HDV engines. An alternative after-treatment method - NO_x adsorption - requires the engine to be run periodically with a rich air:fuel ratio, which increases fuel consumption. As a consequence, SCR tends to be used in preference to NO_x adsorption in HDV applications. No manufacturer is currently planning to introduce NO_x-adsorption technology in the European HDV market.

Effects on emission maps

The main issue relating to the determination of emission maps for Euro IV and Euro V engines was whether the technologies used would have a varying efficiency over the engine map. High fuel efficiency is the main aim for HDV engine manufacturers, and is crucial for competitiveness in the sector. For Euro IV and Euro V vehicles, it must also be assumed that manufacturers will continue to focus on fuel efficiency for low investment and running costs. Consequently, the following assumptions were made in ARTEMIS for Euro IV and Euro V engines (Rexeis *et al*., 2005):

(i) It was assumed for the development of the basic emission maps that DPFs would not be widely used in Euro IV and Euro V engines. A reduction in PM emissions will be achieved via optimised fuel injection and combustion processes, in combination with an oxidation or particulate catalyst, but without the application of a DPF. Available measurements from a Euro V SCR test engine[11] have shown PM emissions 40% lower than the Euro V limit value, over both the ESC and ETC cycles.

(ii) In the ARTEMIS model, the option of 'DPF-technology' can be chosen, which assumes a reduction in PM mass of approximately 90%, and an increase in fuel consumption of 3%, compared with the relevant basic engine emission map.

(iii) For NO_x emissions, the basic technology for compliance with the Euro IV limits will be SCR. EGR with PM-cats will be applied mainly to some smaller vehicles. The potentially different pollutant emission behaviour associated with SCR and EGR cannot be properly assessed at present. All Euro V HDVs will use SCR technology.

(iv) The application of SCR will be optimised in the regions of the engine map covered by the type approval tests (ETC and ESC). It is unlikely that emission-reduction strategies (*e.g.* urea dosing with SCR) will be applied to all regions of the engine map where there is no urgent requirement to do so, as this would imply penalties in terms of fuel consumption and cost.

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[11] Measurements of a Euro V test engine with SCR technology, and the corresponding basic Euro III engine, were made available from the PARTICULATES project.

(v) OBD systems will be installed, limiting NO_x emissions everywhere on the engine map to 5 g/kWh for Euro IV and to 3.5 g/kWh for Euro V[12]. Without such control systems, especially at low engine speeds, much higher NO_x levels than currently indicated by the emission factors could emerge. This could drastically increase the emission factors for urban and rural driving. For this reason, the in-use control of future-technology vehicles seems to be necessary.

(vi) The application of the SCR system allows for higher raw exhaust NO_x emissions. This enables further optimisation of fuel consumption (earlier injection timing). Compared with Euro III engines, reductions of around 7% (for Euro IV engines) and 5% (Euro V engines) are predicted.

The actual effects applied in PHEM may be rather optimistic, since rational electronic engine control strategies and a restrictive OBD are assumed for all vehicles everywhere in the engine map. These assumptions are not reflected completely in the actual type approval Directive for Euro IV and Euro V.

3.4.3 Alternative fuels

Currently, the only alternative fuels that have reached appreciable shares of the HDV market are compressed natural gas (CNG), bio-diesel and liquefied petroleum gas (LPG). Emission factors had to be estimated from the available literature. For modern LPG-fuelled HDVs, no satisfactory data on emission levels were found, so no emission factors could be provided (Rexeis *et al*., 2005).

Compressed natural gas (CNG)

CNG is used in SI engines with special fuel injection. Early CNG engines were operated almost exclusively stoichiometrically, and were able to reach very low emission levels for NO_x, CO, HC and PM, at least when new. Durability tests for modern vehicles are not commonly available, and some early examples showed poor emission stability over time. A disadvantage of CNG is the much lower fuel efficiency compared with diesel engines. Energy consumption from stoichiometric CNG engines is at least 10% higher than that for diesel HDVs. For this reason, modern CNG vehicles tend to equipped with lean-burn engines. A disadvantage of the lean-burn engine is that the catalytic converter does not reduce NO_x emissions during lean-burn conditions. Thus, as with diesel engines, the same principle trade-off between NO_x and fuel efficiency occurs. Therefore, the use of CNG does not necessarily provide benefits in terms of NO_x emissions.

Table 17 summarises the emission levels of modern CNG engines as a percentage of the Euro III emission factors. Compared with Euro IV and Euro V diesel engines the advantages of CNG would diminish, since the Euro IV and Euro V limits require clear reductions in NO_x and PM emission levels. Of course, further emission reductions could also be achieved for CNG vehicles (Rexeis *et al*., 2005).

Table 17: Emission levels of a CNG-fuelled HDV relative to the emission factors for a Euro III HDV (ratios based on real-world cycles; [g km^{-1}] for emission and fuel consumption values).

Technology	NO_x	PM	CO	THC	NMHC	FC
Diesel Euro III	100%	100%	100%	100%	100%	100%
CNG EEV [a]	85%	10%	15%	300%	25%	120%

a Enhanced Environmental Friendly Vehicle with lean-burn concept.

Bio-diesel

For the HDV sector, compliance with the European Biofuels Directive – stating that a 5.75% share of the fuel used in 2010 must be biofuel – may, to a large extent, be realised by the use of bio-diesel. If the existing Directives on fuel quality are met, bio-diesel can be used in many HDVs without major modification, as long as important criteria for the storage of bio-diesel and the method for replacement of fossil diesel are considered. While the blending of up to 5% bio-diesel does not affect emission levels very much, the use of pure bio-diesel certainly has an effect on the emission behaviour of diesel engines. Measurements indicate an increase in NO_x emissions of 10-20% but reduced PM emissions (although for some vehicles and test cycles

[12] In the low-load engine map area, this limitation will probably not be practicable, because very low absolute NO_x emissions have to be detected by the OBD system.

an increase in PM was observed). Also, the source of bio-diesel (vegetable oil from rape seed, palm, soybean, used cooking oil, animal fat from tallow, *etc*.) influences the emission changes resulting from fossil fuel being substituted by bio-diesel. Therefore, the emission changes associated with a shift from fossil diesel to bio-diesel given in Table 18 have to be seen as average estimates.

Table 18: Emission levels of HDVs driven with bio-diesel instead of fossil diesel (ratios based on g km^{-1} emission and fuel consumption values).

Fuel	NO_x	PM	CO	THC	NMHC	FC
Conventional diesel (Euro III)	100%	100%	100%	100%	100%	100%
Bio diesel [a]	120%	80%	75%	60%	50%	115%

a Average ratios if fossil diesel is replaced by bio-diesel.

3.4.4 Effects of engine deterioration and maintenance

Emissions from HDVs are influenced by the age of the engine and the maintenance condition. In order to determine whether this influence had to be taken into account in the ARTEMIS model, the effects of engine deterioration and maintenance on emissions were assessed using extensive data on pre-Euro I to Euro III vehicles from the Dutch and German in-use compliance programmes. For Euro I and Euro II vehicles it was assumed that maintenance would result in the changes shown in Table 19. The overall effect was calculated by multiplying the percentage of vehicles needing maintenance by the average reduction in emissions imposed by applying the necessary maintenance. The reductions were weighted for potential differences in fuel consumption as a result of maintenance, since this would have had a secondary influence on the emission level during the tests.

Table 19: Average emission effects (% change) as a result of maintenance activities, and the expected overall effect on average Euro I and Euro II fleet.

Percentage of vehicles needing maintenance	Euro I	Euro II
	52%	33%
Average effect on PM	-15%	-23%
Average effect on NO_x	-3%	-2%
Average effect on CO	-17%	-4%
Average effect on HC	2%	-11%
Overall effect on PM	-8%	-7%
Overall effect on NO_x	-1%	-1%
Overall effect on CO	-9%	-1%
Overall effect on HC	1%	-4%

For Euro III vehicles equipped with electronic fuel pumps and an engine management system, the condition of the fuel injectors can be expected to be the main issue. However, none of the Euro III vehicles tested in ARTEMIS had injector problems. On the other hand, these vehicles were relatively new, with odometer readings not exceeding 180,000 km. Based on the Euro II data, around 20% of the vehicles had problems relating to the injectors, resulting in an average PM increase of around 18%. Over the vehicle fleet this equates to an average increase of 3-4% for Euro II vehicles, and probably less for Euro III vehicles. For the other pollutants the increase in emissions from Euro III vehicles is likely to be insignificant (Rexeis *et al*., 2005).

3.4.5 Effects of fuel quality

An approach was proposed for including fuel quality effects in the ARTEMIS model (Rexeis *et al*., 2005 and references therein), whereby a percentage change in emissions was applied to the basic emission factors. This approach required a baseline fuel to be defined, from which changes could be evaluated. Baseline fuel properties for pre-Euro I, Euro I and Euro II engines were taken from the Worldwide Diesel Fuel Quality Surveys. Baseline fuel properties for Euro III engines were defined based on the average quality of the corresponding fuels used in the ARTEMIS tests. Baseline fuel properties for Euro IV and Euro V engines were estimated based on the requirements of vehicle and engine manufacturers, as published in the latest World–Wide Fuel Charter. The proposed baseline fuel properties are summarised in Table 20.

Table 20: Baseline fuel properties (Rexeis *et al*., 2005).

Emission legislation	Density (kg/m^3)	Cetane number	Cetane difference	Poly-aromatics (%)	Total aromatics (%)	T10 (^oC)	T50 (^oC)	T95 (^oC)	Sulphur Content (ppm)	Oxygen content (%m)
Pre-Euro1	835	51	0	6	25	205	260	345	1500	0
Euro I	835	51	0	6	25	205	260	340	1300	0
Euro II	830	53	0	5	20	205	260	340	300	0
Euro III	830	53	0	4	20	210	265	340	40	0
Euro IV	830	55	0	2	15	210	265	340	10	0
Euro V	830	55	0	2	15	210	265	340	5	0

The percentage changes in emissions were calculated using the models described below. These could then be applied to the emission factors estimated by the main model, based on the baseline fuels. According to Rexeis *et al*. (2005) the most comprehensive investigations of the effects of fuel properties on HDV emissions have been carried out within the scope of the following programmes

- European programme on emissions, fuels and engine technology (EPEFE).
- US EPA heavy-duty engine working group programme (EPA-HDEWG).
- US diesel emission control – sulphur effects programme.
- USEPA project on modelling effects of diesel fuel properties on heavy-duty engine emissions (‘New EPA’).

Rexeis *et al*. (2005) recommended the use of the following models:

- The EPEFE model for assessment of fuel effects on CO and PM emissions.
- The New EPA model for assessment of fuel effects on HC and NO_x emissions.

The forms of these models are shown in Table 21.

Table 21: EPEFE and new EPA regression equations.

Pollutant	EPEFE [g/kWh]	New EPA, [g/hp h]
CO =	$2.24407-0.00111\boldsymbol{D}+0.00007\boldsymbol{P}-0.00768\boldsymbol{C}-0.00087\boldsymbol{T95}$	
HC =		$\text{Exp}(5.32059-0.1875\boldsymbol{CN}+0.001571\boldsymbol{CN}^2-0.0009809\boldsymbol{T10}-0.002448\boldsymbol{T50}-0.1880\boldsymbol{CD}+0.003507\boldsymbol{CN}*\boldsymbol{CD})$
NO_x =		$\text{Exp}(0.50628-0.002779\boldsymbol{CD}+0.002922\boldsymbol{A}+1.3966\boldsymbol{G}-0.0004023\boldsymbol{T50})$
PM =	$(0.06959+0.00006\boldsymbol{D}+0.00065\boldsymbol{P}-0.00001\boldsymbol{C})*[1-0.000086(450-\boldsymbol{S})]$	

D – density, kg/m^3; ***G*** – specific gravity; ***P*** – poly-aromatics content, % m; ***A*** – total aromatics content, % vol; ***C*** – cetane number; ***CN*** – natural cetane number; ***CD*** – cetane difference due to additising; ***S*** – sulphur content, ppm; ***T10*** – T10 temperature, ^oF; ***T50*** – T50 temperature, ^oF; ***T95*** – T95 temperature, ^oC.

3.5 Effects of different test parameters: two-wheel vehicles

The ARTEMIS work on emissions from two-wheel vehicles is summarised in the report by Elst *et al.* (2006). One of the main objectives was to develop a set of representative emission factors, and an extensive measurement programme was conducted, involving tests on 90 motorcycles. Before the measurement programme began a round robin test programme was carried out to check whether the results over different driving cycles were reproducible when measured in different laboratories, and to identify potential measurement difficulties. The sensitivity of emissions to fuel properties and inspection and maintenance was also examined. This work is relevant to the development of emission factors for two-wheel vehicles in the UK.

3.5.1 Round robin test programme

Bremmers *et al.* (2001) described the round robin test programme. Where reference is made to Directive 97/24/EC, the status of that Directive in 2001 is implied. The measurement programme was carried out over a period of 14 months. Two different motorcycles were used: a two-stroke scooter with no exhaust gas after-treatment and a four-stroke ‘sports bike’ with a three-way catalyst. The round robin began at TNO in Delft. The motorcycles then travelled to KTI (Bucharest), FHB (Biel), TÜV-Nord (Hannover) and back to TNO. The petrol fuel used in the programme was similar at all laboratories.

The following general conclusions and recommendations were drawn from the round robin tests:

- The chassis dynamometer emission measurements carried out on motorcycles in the different laboratories agreed, depending on the pollutant, within a range of about ±25%.
- The range of emission levels for two-wheel vehicles can be much wider than that for modern passenger cars (*e.g.* 0.3-30 g km^{-1} for CO). Tests on vehicles with comparable emission levels should be conducted during the same session using appropriate analyser ranges and tunnel flow rates. Directive 97/24/EC prescribes that the dilution air should be analysed using the same analyser range as that used for the diluted exhaust gas. Since the selected range for analysing the exhaust gas could be very high, zero values might be obtained for the dilution air. The dilution air should be analysed over a more suitable (lower) range, and the analyser should be calibrated over both the selected ranges before the bags are analysed.
- Brake load settings can be relatively small and therefore difficult to simulate. A single, easy-to-use method should be defined for brake load settings and analyser calibration procedures.
- Highly dynamic test cycles, in combination with a high power:mass ratios and/or the presence of electronic engine management systems or exhaust gas after-treatment, may result in poor repeatability.
- Improvement to the running resistance table prescribed by Directive 97/24/EC[13] should be made, since the brake load settings are not suitable for high-speed cycles.
- Test drivers should be acquainted with the cycles to be driven and the specific behaviour of the test vehicles.
- Improvements to the response times in brake load simulation are required, as test cycles will become more dynamic.
- There should be further investigation of the poor repeatability for modern vehicles equipped with three-way catalysts.

3.5.2 Vehicle categorisation

Because of the wide variation in vehicle weight, engine capacity, engine type (two- or four-stroke) and exhaust gas after-treatment technology, it is important to define appropriate vehicle categories for emission testing purposes. The main parameters which were considered are listed below (Rijkeboer, 2000).

Engine capacity: Since 'mopeds' (< 50 cm^3) were not taken into account within ARTEMIS, the following distinction was made: 50-125 cm^3, 126-250 cm^3, 251-500 cm^3, 501-750 cm^3, 750-1000 cm^3 and > 1000 cm^3.

Engine type: Throughout Europe two-wheel vehicles are equipped with two-stroke and four-stroke petrol engines (except for one diesel model and a few electric models). For the purpose of categorising

[13] Directive 2003/77/EC contains a new running resistance table.

motorcycles, a distinction between these two main engine types was therefore required. Because two-stroke engines tend to have a small engine capacity, and are mostly used on scooters, the distinction was only applied to motorcycles with an engine capacity of less than 250 cm^3.

Exhaust gas after-treatment: In time, more two-wheel vehicles will be equipped with exhaust gas after-treatment systems (*e.g.* oxidation catalyst, 'coated tube' or three-way catalyst), but relatively few data were available to evaluate their performance under real-world driving conditions. For categorisation purposes, a distinction between catalyst and non-catalyst motorcycles was therefore applied.

Age, mileage and legislative category: The age of a vehicle is linked to its technology level and the emission legislation to which it conforms.

Model: Different types of motorcycle model are currently available on the market. Since each type of motorcycle has its own characteristics, a broad division between the following model classes was established: 'scooters', 'off-road', 'enduro', 'touring', 'choppers', 'sports' and 'super-sports'.

3.5.3 Other issues

During the round robin tests, differences were apparent between the ways in which tests were conducted at the different laboratories (Bremmers *et al.*, 2001). These were addressed as follows:

Dilution ratio: Depending on the motorcycle to be tested, the test cycle to be driven, and the analyser ranges, a suitable dilution ratio should be chosen in order to measure all pollutants with sufficient accuracy.

Procedure for analysing bag samples: The procedure to be used to analyse the bags (for dilution air as well as for exhaust gas) was improved following the recommendations of the round robin programme. A flow chart describing the procedure for emission bag analysis was developed to ensure common understanding.

Vehicle condition: Each motorcycle had to have been driven for at least 1,000 km before the test, but otherwise vehicles were tested in the 'as received' condition.

Deceleration phases: In the type approval test, specific operation is required during deceleration phases. However, this specific operation might not be valid for real-world operation, and therefore was not be applied during such cycles.

Engine starting, restarting and emission sampling: The procedure was a combination of both European and US Directives. The pre-conditioning cycle conducted before the type approval cycle included an engine start. All other test cycles were started with a running engine. Again, a detailed procedure was developed.

Choke operation: A specific procedure was included for choke operation, since most of the motorcycles tested were still equipped with a manual choke.

Data processing: A test report template was developed to ensure consistency.

3.5.4 Driving cycle effects

CO emissions were similar over type approval and real-world test cycles when the emission levels were above 20 g km^{-1}. For some cases below 20 g km^{-1} CO, emissions over the real-world cycles were generally higher than those over the type approval cycle. For Euro 2 motorcycles CO emissions over the real-world test cycles were much higher than the emissions over the type approval test cycle. When HC emissions were higher than 6 g km^{-1} (*i.e.* older motorcycles), the emission levels over type approval cycles and real-world cycles were similar. Most of the test vehicles had higher HC emissions over real-world test cycles. In general, NO_x emissions were higher during real-world test cycles, probably as a result of the higher accelerations and engine load. Compared with the type approval test cycle, CO_2 emissions were lower over the FHB 'Zentrum' real-world cycle, even though the latter was more dynamic and had a higher average speed. However, the FHB Zentrum cycle contained fewer and shorter stops, and accelerations from zero speed influenced the CO_2 emissions. CO_2 emissions over the ARTEMIS urban test cycle were, in general, slightly higher than emissions over the type approval test cycle.

It appeared that some of the tested motorcycles might have been calibrated for the type approval cycle. Another general conclusion was that the differences in emissions between the real-world test cycles (FHB Zentrum and ARTEMIS urban) were not very large for CO, HC and NO_x. The emission results over the urban test cycles (ARTEMIS Urban, FHB Zentrum and Peripherie) and rural test cycles (ARTEMIS rural and FHB Überland) were also assessed.

For urban cycles, on average, CO, HC, NO_x and CO_2 emissions were lower over the FHB cycles compared with the ARTEMIS urban cycle. The FHB Zentrum results were slightly lower than the ARTEMIS urban results. However, the average speed and RPA did not differ greatly, which indicates that other parameters might be related more closely to emissions (*e.g.* percentage of stops). The higher average speed but less dynamic FHB Peripherie test cycle emission results were the lowest for all pollutants, probably as a result of the lower number of rapid accelerations. For rural cycles the CO, NO_x and CO_2 emissions over the FHB Überland cycle were lower than those measured over the ARTEMIS rural cycle. However, HC emissions were slightly higher. Compared with the urban test cycle results, the results over the rural test cycles were more variable. The general conclusion was that emissions measured over the ARTEMIS urban and rural cycles were higher than those measured over the FHB cycles. Apart from the results for a few specific motorcycles, on average the emissions measured over the various test cycles were of a similar order of magnitude. However, for newer vehicles the differences between type approval and real-world cycles are increasing.

3.5.5 Laboratory effects

Due to restrictions with regard to the motorcycles that were available for testing and the requirement to select vehicles in order to meet the categorisation that was drawn up, the composition of the vehicles tested in the various laboratories differed. Nevertheless, general conclusions could be drawn from the average results of the laboratories:

- CO and HC emissions differed considerably between the laboratories. However, the averages calculated for the four-stroke motorcycles tested at TNO and TÜV-Nord showed similar levels for most vehicle classes.
- NO_x emissions were very low, and generally well below the Stage 1 limit of Directive 97/24/EC. The conclusions that were derived for CO and HC were also valid for NO_x.
- Average CO_2 emissions showed a similar trend when comparing the values of the different laboratories. In addition, the absolute averages of the laboratories were closer to each other than for CO, HC and NO_x.
- The levels of average fuel consumption were similar in the different laboratories for all vehicle categories. For two-stroke vehicles the high HC emissions had a significant effect on fuel consumption.

Given the variability in emissions, it was hard to draw any conclusions about laboratory comparability. Nevertheless, the results measured at the different laboratories provided an indication of average emission levels and fuel consumption for the twelve defined engine capacity/type categories. In addition, the results proved to be reliable and may therefore be used as the basic set to be applied for the purpose of emission model development.

3.5.6 Effect of fuel properties

Additional measurements were carried out by KTI to address the effects on emissions of fuel properties. In total five motorcycles were tested. The vehicles had a wide range of engine capacities and physical dimensions, but none of them was equipped with an exhaust gas after-treatment system. The motorcycles were tested over seven driving cycles, and using two different fuels - one fuel which met current requirements and another which complied with near future requirements. As the measurements were conducted at KTI, Hungarian market fuel was selected as the current fuel. The selected future fuel met the requirements laid down for Category 4 in the World Wide Fuel Charter[14] (WWFC, 2002). The principal differences between these fuels were sulphur content (23 ppm for Hungarian market and 3.4 ppm for WWFC4 fuel), olefins (11.2 against 0.4 Vol-%), aromatics (31.9 versus 26.5 Vol-%) and oxygen content (0.58 against 1.74 Vol-%).

The results of the fuel property tests were summarised in a detailed report by Kis *et al*. (2005). The main conclusions were as follows:

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

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

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

3.5.7 Effect of inspection and maintenance

The effects of inspection and maintenance on exhaust emissions from 25 motorcycles were investigated in a project financed by CITA. The results of the CITA project are summarised by Elst *et al*. (2002).

Table 22 gives the number of vehicles tested before and after maintenance - also divided by legislative category - and the average, minimum and maximum improvements that were calculated for all test cycles over which measurements were conducted. Note that negative values represent increases in emissions relative to the measurements conducted before maintenance. The main conclusion was that the sample sizes were too small for the data to be employed for predictive purposes. In addition, the minimum and maximum values show significant variation. This implies that the effect is also related to the test cycle that is used.

Table 22: Maintenance conducted and improvement on CO, HC, NO_x, ‘ultimate’ CO_2 and fuel consumption.

Type of maintenance	No. of vehicles		Average	Minimum	Maximum
	Pre-Euro 1	Euro 1			
CO improvement					
Adjustment of carburettor	2	1	24%	15%	33%
Oil, air and oil filters	1	-	11%	8%	14%
Change of battery	-	2	204%	49%	358%
Oil, air and oil filters, adjustment of carburettor	1	-	-8%	-10%	-6%
HC improvement					
Adjustment of carburettor	2	1	22%	16%	26%
Oil, air and oil filters	1	-	15%	4%	26%
Change of battery	-	2	10%	-13%	33%
Oil, air and oil filters, adjustment of carburettor	1	-	-18%	-20%	-17%
NO_x improvement					
Adjustment of carburettor	2	1	44%	-28%	103%
Oil, air and oil filters	1	-	23%	-14%	59%
Change of battery	-	2	299%	101%	497%
Oil, air and oil filters, adjustment of carburettor	1	-	-1%	-4%	1%
Ultimate CO_2 and fuel consumption improvement					
Adjustment of carburettor	2	1	19%	10%	31%
Oil, air and oil filters	1	-	0%	-1%	1%
Change of battery	-	2	18%	5%	32%
Oil, air and oil filters, adjustment of carburettor	1	-	-2%	-3%	-2%

The effects of changing the battery were found to be significant for CO, NO_x, ultimate CO_2 and fuel consumption. However, the number of occurrences in reality might be very low since a broken battery - which causes much inconvenience for the driver of the motorcycle – will probably be replaced quickly.

4 Summary, conclusions and recommendations

4.1 Evaluation of driving cycles

4.1.1 Summary

Comparisons were made between the characteristics of several sets of data relating to vehicle operation: (i) a large database of real-world driving patterns recorded for vehicles in normal operation on UK roads, (ii) a Reference Book containing 256 driving cycles from various countries, (iii) the driving cycles in the UKEFD, (iv) the WSL driving cycles for cars and LGVs and (v) the FiGE driving cycles for heavy-duty vehicles.

National statistics indicate that relatively few vehicles on UK roads are travelling at speeds below 20 mph. This implies that for emission inventories the accurate characterisation of emissions at very low speeds is likely to be less important than accurate characterisation at other speeds. However, accurate emission factors at low speeds remain important for local air quality assessment purposes.

Cars and LGVs

For cars, the real-world driving patterns, the Reference Book driving cycles and the UKEFD cycles have broadly similar average speed distributions. The real-world driving patterns have average speeds ranging from just above zero to around 118 km h^{-1}. However, the upper limit was artificially low as drivers were instructed to obey speed limits, and it is clear that much higher speeds can actually occur. The driving cycles in the Reference Book and UKEFD cover a similar range of average speeds, but have a maximum average speed of 130 km h^{-1}. The ARTEMIS sub-cycles have average speeds clustered around 20, 60 and 100 km h^{-1}. Some of the low-speed Reference Book/UKEFD driving cycles were found to have relatively high average accelerations and average decelerations which are not apparent in the real-world driving patterns.

The WSL cycles, which have been routinely used to measure emissions in UK test programmes, cover much of the speed range observed in the driving patterns. The national statistics show that significant number of cars on the road are travelling at speeds which are higher than the maximum average speed of the WSL cycles (112 km h^{-1}), and therefore emissions from such cars are not routinely covered in emission test programmes. The WSL cycles are also generally less ‘aggressive’ than driving patterns in the real world. In contrast, the ARTEMIS sub-cycles were generally slightly more ‘aggressive’. On the whole, the characteristics of the real-word driving patterns appear to be well-represented in the UKEFD as a whole.

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

There are a number of possible explanations for these observations relating to the WSL cycles. For example, the driving patterns used to develop the WSL cycles were logged using a variety of vehicles, ranging from small, low-powered cars to large, powerful cars, and the driving pattern data were then analysed to produce a set of average cycles which were suitable for all cars. These average cycles were subsequently adjusted on a chassis dynamometer, and gear-change points added to produce three different cycles for small, medium and large cars (the speed traces remained very similar). In addition, the driving patterns were recorded on roads previously used by Warren Spring Laboratory for on-board emission testing work. The cars were driven by an ex-employee of WSL who was experienced in the test routes used. The other test programmes at TRL have used a variety of drivers – mainly TRL staff of various age and driving experience and also external drivers. The differences may therefore be due to different driving styles of the various drivers.

HGVs

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

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

Buses and coaches

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

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

4.1.2 Conclusions and recommendations

In the development of emission factors for the UK, an attempt should be made to use driving cycles which are as representative as possible of real-world driving in the UK, and there appears to be some scope for improving the current approach.

A distinction needs to be made between the improvement of the current emission factors in the UKEFD and the requirements with respect to future tests. The current emission factors relate to existing[15] types of vehicle, based on tests which have already been conducted. This work has shown that large numbers of test results are available for some vehicle categories, and the tests cover a wide range of conditions. For future vehicle types, emission model developers clearly do not have the benefit of this existing information, and further testing will be required. A simpler range of test conditions therefore needs to be defined to allow the derivation of representative emission factors in a cost-effective manner. There is a need to specify a small number of driving cycles which are as representative as possible of real-world driving.

The representativeness of the driving cycles used to generate emission factors should be tested by comparison with a large database of real-world driving patterns (ideally, not the driving patterns used to develop the driving cycles). Such comparisons need to take into account not only the typical average speeds of vehicles on the road, but also the dynamics of the driving patterns. This approach has not been used in the past, and the work reported here represents the first stage in the process.

The conclusions and recommendations given below have been drawn from this part of the work. These will be carried forward into Task 2.

Existing emission factors

A re-assessment of the driving cycles currently used in the UKEFD has been conducted. This effectively equates to an evaluation of the representativeness (in terms of driving characteristics alone) of the existing emission factors in the UKEFD. Although many driving cycle parameters were calculated, the assessment was mainly based upon average speed, average acceleration and average deceleration. The following recommendations apply to the improvement of the existing emission factors in the UKEFD:

- For cars, the assessment has indicated that the driving cycles in the existing UKEFD adequately cover the range of driving characteristics observed in the real world. However, a small number of UKEFD driving cycles appear to have average positive and negative accelerations which are outside the range of real-world conditions. The possibility of replacing these cycles with other cycles from the Reference Book, and using the latter to fill gaps in the UKEFD, should be further investigated in Task 2.

[15] In this context, 'existing' types can probably be assumed to be vehicles up to and including Euro III, as measurements on Euro IV vehicles are much more limited.

- For LGVs the database of real-world driving patterns is more limited, although the cycles used in the current UKEFD appear to cover the range of driving characteristics which are likely to be encountered. However, as with cars some UKEFD cycles may have average accelerations which are not realistic for the UK. This needs to be investigated further.
- In the case of HGVs, some of the low-speed UKEFD driving cycles have relatively high accelerations which are not apparent in the real-world driving patterns (specifically the Millbrook Heavy Duty: urban cycle and the three Millbrook Westminster Dust Cart cycles). Some of the UKEFD cycles have more rapid decelerations than the real-world driving patterns. In particular, one of the high-speed UKEFD cycles (Millbrook Heavy Duty: motorway) has a very high average deceleration.
- For urban buses, coaches and heavy goods vehicles the range of available driving cycles is relatively limited. Urban buses operate at relatively low speeds, and may be unable to attain the higher speeds required for some of the cycles. Coaches, on the other hand, are likely to operate at higher motorway speeds. Urban buses and coaches should therefore be treated separately when deriving emission factors, and more representative driving cycles for these vehicle classes should be used in the derivation of the future UK emission factors.

Implications for future tests

- The WSL cycles do not appear to reproduce the aggressiveness of driving for cars and LGVs, and do not cover the highest speeds encountered on the road. A more representative set of driving cycles should therefore be considered for future testing. Alternatively, the WSL cycles could be retained, but supplemented with some high-speed cycles, and cycles which have higher average accelerations and decelerations.
- Similar conclusions were drawn concerning the FiGE cycle and heavy-duty vehicles. The FiGE cycles do not cover low average speeds, and do not reflect the speeds of older, unrestricted vehicles. Although some of the real-world driving patterns have average speeds lower than 10 km h^{-1}, such low speeds are not represented in the FiGE cycle (which has a minimum average cycle speed of 23 km h^{-1}). The higher-speed FiGE cycles (suburban and motorway) also appear to have low average accelerations compared with the real-world driving patterns. In addition, the higher-speed FiGE cycles have less rapid decelerations than the real-world driving patterns. Again, a more representative set of driving cycles should be considered for future testing.
- For all vehicle types it appears that the driving cycles contained in the Reference Book provide a good level of coverage of different aspects of vehicle operation. It therefore appears that any new emission factors for use in the UK could be based on driving cycles which are included in the Reference Book, and there is no need for new cycles to be developed.

These conclusions and recommendations are only based on an assessment of driving cycle parameters and are therefore essentially speed-based. Parameters such as engine speed and engine load have not been taken into account as there are few real-world measurements which would enable corresponding assessments to be made.

4.2 Review of emission test parameters

4.2.1 Summary

Cars

The ARTEMIS passenger car study was designed to examine the influence of many different parameters on the measurement of emission factors. During the test programme, it was found that some parameters did not exert an influence over the measured emission factors. For other parameters, an influence was apparent, but could not be quantified. Finally, some parameters had a clear and quantifiable influence.

There was no statistically significant influence on emission measurements for the parameters listed in Table 23. This does not mean that these parameters have no influence on the emission measurements, but only that there is no currently known influence, taking into account the small data sample or the contradictory results. The parameters having a qualitative influence are summarised in Table 24. In the case of parameters having a clear, statistically significant and quantifiable influence on emissions (Table 25), it was possible to normalise emission measurements from different laboratories using correction factors.

Table 23: Parameters having no influence on emissions.

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

Table 24: Parameters having a qualitative influence on emissions.

Parameter		Findings	Recommendation
Driving cycle parameters	Influence of the driver	Only CO_2 emissions were significantly higher with a human driver than with a robot driver, but the difference could not be explained by the driving characteristics. The robot did not give more stable emissions, and some driving cycles are too aggressive for it.	A human driver can be used for emission tests. Tolerances of ± 2 km h^{-1} and ± 1 s should be applied. A test should be accepted if it is within these bands for > 99% of the time, and if the driven distance is within 1% of the reference distance. Notes should be made of failures due to insufficient power, wheel slip, *etc.*, or if the engine stalls. In all other cases a test should be rejected.
Vehicle-related parameters	Technological characteristics	The type approval category and the fuel have a clear influence on the emissions, and the engine capacity in some cases. No correlations between emission behaviour and specific emission control technologies were found within the same type approval category.	The addition of specific technological characteristics to models will not improve the accuracy of emission databases for conventional cars up to Euro 4
	Vehicle preconditioning	The preconditioning conditions have an influence in some cases, but rarely for modern close-loop vehicles.	A 10-minute cycle at a constant speed of 80 km h^{-1} can be considered as the most suitable preconditioning cycle.
Vehicle sampling method	Method of vehicle sampling		Where possible, test vehicles should be selected from an 'official' list. The real-world distributions of fuels, emission standards, vehicle size, maximum engine power, mileage should be taken into account in the selection of vehicles.
	Vehicle sample size	The variability between vehicles is a significant factor, together with the emitter status. It is not possible to know the emitter status before measurement, and the high variability between vehicles of a same category requires that cars are samples randomly within a category.	A minimum sample of 10 vehicles should be used to derive emission factors for a given vehicle category which are representative of an average vehicle behaviour.
Laboratory-related parameters	Dynamometer settings	The dynamometer settings have a clear influence on all emissions, but are only significant for CO_2 and fuel consumption, and on NO_x for diesel vehicles. Although only few effects were found significant, they still require an accurate simulation of the actual road load.	It is recommended that emissions measured with altered chassis dynamometer settings are not used to derive emission factors. For emission factor development, road load information derived from the coast-down method performed by the laboratory and inertia setting should be as close to the on-road values as possible.
	Response time		In the development of instantaneous emission models, the emission signals must be corrected for dynamic distortion during measurement.

Table 25: Parameters having a quantitative influence on emissions.

Parameter		Findings
Driving cycle parameters	Driving cycle	The driving cycle has a significant effect on emissions, but it was not possible to design a systematic correction function. However, given the very high diversity of the emission data collected in ARTEMIS, and the large range of the corresponding driving cycles, it was not possible to develop emissions factors without managing this cycle influence. A harmonisation approach was developed, based on the similarities between cycles from a kinematic perspective. This enabled the grouping of the hot emission data into coherent groups.
	Gear-shift behaviour	It was possible to classify gear-shift strategies according to CO_2 emissions (the only pollutant systematically affected). The most polluting strategy was one in which gear changes were defined for given engine speeds. The least polluting strategy was one in which gear changes were defined for given vehicle speeds.
Vehicle-related parameters	Emission degradation	The influence of mileage on petrol-fuelled vehicle emissions depends on the pollutant, the type approval category (or emission standard) and the average speed. Mileage has no influence on CO_2 emissions, but increases CO, HC and NO_x emissions of petrol cars: Between 0 km and 100,000 km, these emissions increase by a factor 3.6 in average for Euro 1 and 2 vehicles, and by 15% for Euro 3 and 4 vehicles. No mileage effect was observed for diesel vehicles. No effect of maintenance was observed on the emission level, either as a consistent before-after maintenance improvement or as a function of mileage.
Laboratory-related parameters	Ambient temperature	An ambient temperature effect was observed for all pollutants and most vehicle classes.
	Ambient humidity	The influence of the ambient humidity was observed only for NO_x and for some vehicle classes.
	Dilution ratio	A higher dilution ratio increases only diesel PM emissions.

HDVs

The conclusions drawn from the ARTEMIS work on HDVs included the following:

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

Two-wheel vehicles

The conclusions drawn from the ARTEMIS work on two-wheel vehicles included the following:

- When real-world passenger car and motorcycle driving were compared, the main differences were at higher average speeds. At higher speeds the driving of two-wheel vehicles is much more dynamic than that of passenger cars due to the relatively high power:mass ratio.
- The ARTEMIS cycle for passenger cars is very dynamic, and for urban driving has appropriate values of RPA and average acceleration for motorcycles.
- NO_x emissions from two-wheel vehicles were very low over the type approval cycle.
- For motorcycles having high CO and HC emission results, the differences between the results over the type approval and real-world cycles were negligible. As emission levels over the type approval test decrease, the differences increase. However, this conclusion is not valid for NO_x. Some of the tested motorcycles were equipped with an exhaust system configuration which appeared to have been specifically calibrated for the type approval cycle.
- Emissions over the ARTEMIS urban and rural parts were higher than emissions over the FHB test cycles, and it appeared that the differences were related to driving dynamics. However, for motorcycles equipped with exhaust gas after-treatment systems (Euro 3), driving dynamics appears to be a less reliable determinant of emissions.
- For the measurements in ARTEMIS a Hungarian market fuel and a fuel meeting the WWFC Category 4 future requirements were selected. With regard to replacing market fuel by fuel that is compliant with WWFC4 requirements:
  - CO emissions were, on average, reduced by 15%,
  - HC emissions decreased by 5%,
  - NO_x emissions were not affected.
  - CO_2 emissions increased by 4%.
  - Fuel consumption was not affected.
- The effects of inspection and maintenance ranged from an adverse effect (emission increase after maintenance) for all pollutants of one of the motorcycles (range -18% to -1%) to very high for two motorcycles which had a faulty battery (range 299% to 10%). The effect of inspection and maintenance on emissions may therefore not be neglected. Although measurements were carried out before and after maintenance for seven motorcycles, the effect was dependent on the type of maintenance that was conducted. Therefore, average adjustment factors were derived to address the effects of inspection and maintenance on emissions.

4.2.2 Recommendations

Cars

When comparing generic and vehicle-specific driving cycles for Euro 2 and 3 vehicles, the use of a generic set of driving cycles leads to a significant underestimation of CO emissions from petrol vehicles and HC and PM from diesel vehicles, and to an overestimation of diesel CO emissions. The generic procedure also leads to an underestimation of CO and HC emissions from small cars and to a slight overestimation of HC and NO_x from the most powerful cars. The use of generic driving cycles for all the cars could therefore lead to errors in emission estimations. Although it would increase the complexity of the test procedure, taking into account vehicle performance by the use of specific driving cycles would lead to an improvement in the quality of the emissions estimates. This is especially important for the most recent cars, which are more sensitive to the test conditions.

Additional test cycles would incur additional time and costs when carrying out emission tests on vehicles. An alternative may be to develop a test cycle (or use a number of existing cycles) that could be broken down into a large number of sub-cycles. If the continuous emissions data are provided, and assuming time delays do not cause a significant error, then the emissions over each sub-cycle could be calculated. This would allow a limited number of test cycles to yield a larger number of data points through which an average speed emissions curve could be fitted.

In ARTEMIS, a hierarchical model was constructed to explain the logarithm of the total emission per cycle as a function of the cycle characteristics. It is not common practice to use the logarithm of the emission - this was justified by the fact that emissions were close to zero with a large coefficient of variation, and because emission results are generally distributed according to a log-normal distribution. It would be of interest to test the application of this approach in the development of the UK emission factors.

The ARTEMIS project identified five parameters for which the effect on emissions could be quantified: These parameters were:

- gear-shift strategy
- vehicle mileage
- ambient air temperature
- ambient air humidity
- exhaust gas dilution ratio.

When compiling an emission factor database correction factors should be applied to the first four of these where possible in order to standardise the data and examples are given in Appendix F.

Although continuous emission measurements can aid the understanding of different effects, there is an additional cost. As emission models are constructed primarily using bag samples, and there remain some artefacts in continuous measurements which are difficult to correct, there appears to be little justification for routinely including continuous emission measurements in the tests used for emission factor development. This recommendation does not apply to *ad hoc* tests for the evaluation of technical and/or policy measures, for which continuous measurements may be beneficial. Where continuous measurements are taken, a high temporal resolution (*e.g.* 10 Hz) is recommended, and some effort ought to be made to correct the continuous signals. For this purpose, a number of experimental settings will need to be recorded.

Two-wheel vehicles

The work conducted within ARTEMIS addressed a wide range of different topics relating to emissions from two-wheel vehicles. Nevertheless, a number of issues remain for future investigation, and some recommendations were given by Elst *et al*. (2006). These included the following.

- The available real-world driving data are limited to certain types of two-wheel vehicle and traffic situation. Real-world data should be recorded for a wider variety of vehicles to obtain more representative driving patterns for specific traffic situations. These data can then be used to develop test cycles or to select driving patterns that are representative of specific traffic situations and vehicle categories.

- A detailed system of vehicle categorisation could be defined for in-use motorcycles. However, the more detailed the categorisation the more vehicles need to be measured to obtain robust emission factors. Therefore, it is recommended that the actual categorisation is adapted to the number of available emission results.

- A detailed measurement protocol which defines the measurement procedure and a standard test report template are vital for assuring comparability of measurements carried out by different laboratories. The presence of a ‘test witness’ who is aware of the measurement procedure and preparative actions, bag analysis and data processing could improve the quality and comparability of the emission data.

- It is recommended that test drivers become acquainted to the test cycle and the specific behaviour of the two-wheel vehicle to be tested.

- It proved difficult to obtain motorcycles from private users for the main measurement programme. Dealers, rental companies and importers proved to be more co-operative in this respect. Two-wheel vehicles obtained from dealers, rental companies and importers are, however, generally well maintained and relatively new. Such vehicles are not recommended when addressing topics such as tampering or deterioration.

- A dedicated measurement programme should be developed to further address fuel effects. The measurement programme should begin by evaluating the fuels that are on the European market. From this assessment, fuels should be selected that are different with regard to specific parameters, and emission tests should be conducted.

- In order to obtain a more detailed understanding of inspection and maintenance, it is recommended that a dedicated test programme should be conducted. The programme should involve measurements before and after maintenance on a significant number of motorcycles. In addition, a distinction might be made between vehicle categories and types of maintenance.
- Another issue of importance might be the effect of mileage on emissions (or ‘durability’). More data relating to this issue may become available in the near future, as it is under discussion in several groups dealing with emission legislation for motorcycles.
- Ideally, an emission modelling methodology should be developed before actual emission measurements take place in order to provide the necessary input data.
- Due to the lack of emission data for current and future emission categories (Stage 2 and Stage 3) emission models will be improved significantly when emission measurements are conducted on vehicles compliant with the legislation.

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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: NAEI method

B1 Overview

The sources of atmospheric emissions from road vehicles, and the pollutants concerned, are:

- Hot exhaust emissions:
  - regulated pollutants[16]: CO, HC[17], NO_x, PM[18]
  - unregulated pollutants
- Cold-start exhaust emissions: CO, HC, NO_x, PM, unregulated pollutants.
- Evaporative emissions: NMVOCs
- Tyre and brake wear: PM
- Road surface wear: PM
- Resuspension: PM

These sources are included in the NAEI, although the inventory is restricted to a limited number of unregulated pollutants (CO_2, SO_2, CH_4, N_2O, benzene, 1,3-butadiene, PAH), and no estimates are made of cold-start emissions of unregulated pollutants.

Emissions from road transport are calculated either from a combination of total fuel consumption data and fuel properties, or from a combination of driving-related emission factors and road traffic data.

Emissions of carbon dioxide and sulphur dioxide from road transport are calculated from the consumption of petrol and diesel fuels and the sulphur content of the fuels consumed. Emissions of CO_2, expressed as kg carbon per tonne of fuel, are based on the H/C ratio of the fuel; emissions of SO_2 are based on the sulphur content of the fuel. TRL equations relating fuel consumption to average speed based on the set of tailpipe CO_2, CO and HC emission-speed equations are used. Total CO_2 emissions from vehicles running on LPG are estimated on the basis of national figures (from DTI) on the consumption of this fuel by road transport. Emissions from vehicles running on natural gas are not estimated at present, although the number of such vehicles in the UK is very small.

The traffic-based emissions calculation methodology is more complex, and is described in the following sections. Emissions of the pollutants NMVOCs, NO_x, CO, CH_4 and N_2O are calculated from measured emission factors expressed in grammes per kilometre and road traffic statistics from the Department for Transport.

B2 Vehicle classification system and activity data

The vehicle classification system used in the NAEI is shown in Table B1. This is a simplified version of the system of classification used in legislation. In the NAEI, an emission function is assigned to each of the classes of vehicle in Table B1. Total emission rates are calculated by multiplying the emission factors by the annual vehicle-kilometres travelled for each of these vehicle classes on different types of roads.

Average emission factors are combined with the number of vehicle kilometres travelled by each type of vehicle on many different types of urban roads with different average speeds and the emission results combined to yield emissions on each of these main road types:

- Urban
- Rural single carriageway
- Motorway/dual carriageway

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[16] The term ‘regulated pollutants’ refers to those pollutants which are subject to exhaust emission (including hot and cold start) or evaporative emission legislation. All other pollutants are termed ‘unregulated’.
[17] Further divided into NMVOCs and CH_4 in the NAEI.
[18] Assumed to be equivalent to PM_{10} in the NAEI.

The current NAEI model provides a classification of vehicle type by vehicle kilometres travelled, and covers the period from 1996 to 2025[19].

Table B1: The vehicle classification used in the NAEI

Vehicle category	Regulation	Vehicle category	Regulation	
Petrol cars by engine size: <1.4 litres 1.4-2.0 litres >2.0 litres	ECE 15.01	Rigid HGVs	Pre-1988	
	ECE 15.02		Pre-Euro I (88/77EEC)	
	ECE 15.03		Euro I (91/542/EEC)	
	ECE 15.04 + failed catalysts		Euro II	
	Euro 1		Euro III	
	Euro 2		Euro IV	
	Euro 3		Euro IV+	
	Euro 4	Articulated HGVs	Pre-1988	
Diesel cars by engine size: <2.0 litres >2.0 litres	Pre-Euro 1		Pre-Euro I (88/77EEC)	
	Euro 1		Euro I (91/542/EEC)	
	Euro 2		Euro II	
	Euro 3		Euro III	
	Euro 3 + particulate trap		Euro IV	
	Euro 4		Euro IV+	
	Euro 4 + particulate trap	Buses and coaches	Pre-1988	
Petrol LGVs	Pre-Euro 1		Pre-Euro I (88/77EEC)	
	Euro 1 (93/59/EEC)		Euro I (91/542/EEC)	
	Euro 2		Euro II	
	Euro 3		Euro III	
	Euro 4		Euro IV	
Diesel LGV s	Pre-Euro 1		Euro IV+	
	Euro 1 (93/59/EEC)	2-wheel vehicles	Moped (2-stroke) <250cc 2-stroke <250cc 4-stroke 250-750cc 4-stroke >750cc 4-stroke	Pre-2000
	Euro 2			
	Euro 3			97/24/EC
	Euro 4			

Assumptions are made about the proportion of failing catalysts in the petrol car fleet. For first-generation catalyst cars (Euro 1), it is assumed that the catalysts fail in 5% of cars fitted with them each year, and that 95% of failed catalysts are repaired each year, but only for cars more than three years in age. Lower failure rates are assigned to Euro 2, 3 and 4 cars manufactured since 1996. The failure rates assumed in the inventory are 5% for Euro 1 vehicles, 1.5% for Euro 2 vehicles, and 0.5 % for Euro 3/4 vehicles.

The inventory takes account of the early introduction of certain emission and fuel quality standards and additional voluntary measures to reduce emissions from road vehicles in the UK fleet. In January 2000, European Council Directive 98/70/EC came into effect relating to the quality of petrol and diesel fuels. This introduced tighter standards on a number of fuel properties affecting emissions. These factors and their effect on emissions were taken into account in the inventory. It is assumed that prior to 2000, only buses had made a significant switch to ULSD, as this fuel was not widely available in UK filling stations.

Freight haulage operators are now looking at incentives to upgrade the engines in their HGVs or retrofit them with particle traps. DETR estimated that around 4000 HGVs and buses were retrofitted with particulate traps in 2000, rising to 10,000 vehicles by the end of 2003. This is taken into account in the NAEI.

Detailed information from DVLA is used on the composition of the motorcycle fleet in terms of engine capacity.

B3 Hot exhaust emissions

Hot exhaust emissions are emissions from the vehicle exhaust when the engine and catalyst have warmed up to their normal operating temperatures. Emissions depend on the type of vehicle, the type of fuel its engine runs on, the driving profile of the vehicle on a journey and the emission regulations which applied when the

[19] Versions of the NAEI are available that also go back to 1990, which is the baseline year for many reporting requirements/protocols.

vehicle was first registered as this defines the type of emission-control technology in use. For hot exhaust emissions, the NAEI uses average-speed emission functions. 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 (represented by a driving cycle). The emission factor is stated in grammes per vehicle-kilometre (g/vkm). Figure B1 shows how a continuous average-speed emission function is fitted to the emission factors measured for several vehicles over a range of driving cycles. Each cycle represents a specific type of driving, and includes stops, starts, accelerations and decelerations.

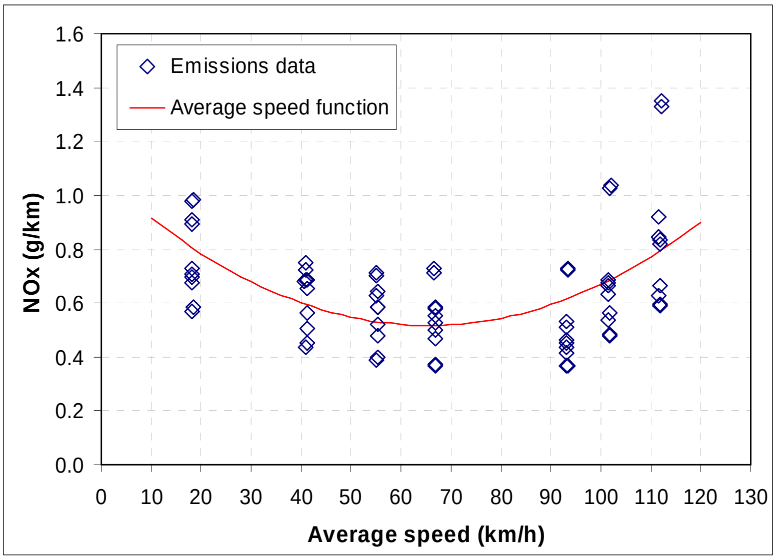


Figure B1: Average speed emission function for NO_x emissions from Euro 3 diesel cars <2.0. The blue points show the underlying emission measurements (Barlow *et al.*, 2001).

For each vehicle category and pollutant, the average speed functions for hot exhaust emissions in the NAEI are expressed in the general form:

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

Where: E = 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 for the pollutants CO, NO_X, PM, HC, benzene, 1,3-butadiene and CO_2, and for the vehicle types shown in Table B1, in a NETCEN spreadsheet (‘vehicle_emissions_v8.xls’)[20]. Coefficients are provided for functions relating emission factors to average speeds between 5 km h^{-1} and 130 km h^{-1} for light-duty vehicles, and between 5 km h^{-1} and 100 km h^{-1} for heavy-duty vehicles.

The emission functions contained within the emission factor database are based upon a large number of measurements from a range of different programmes conducted over a period of several years. The most recent database was compiled in 2002. The database compiled as part of the European Commission MEET project formed the basis of the 2002 database. The MEET database included a considerable amount of data from TRL, derived from various EU- and DfT-funded measurement campaigns. TRL emission data were added from a number of pre- and post-MEET measurement programmes (Boulter *et al.*, 2005).

Emission factors for Euro 1 and Euro 2 vehicles are based on speed-emission factor relationships derived by TRL. The factors for NMVOCs are actually based on emission equations for total hydrocarbons, the group of

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

species that are measured in the emission tests. To derive factors for non-methane VOCS, the calculated g km^{-1} factors for methane were subtracted from the corresponding THC emission factors.

Due to lack of measured data, emission factors for Euro 3 vehicles (and Euro 4 petrol cars) were estimated by applying scaling factors to the Euro 2 factors. The scale factors for light duty vehicles take into consideration the requirement for new vehicles to meet certain durability standards set in the Directives. For heavy-duty vehicles, the emission scaling factors are taken from COPERT III.

Speed-dependent functions provided by TRL for different sizes of motorcycles are used. Motorcycles sold since the beginning of 2000 were assumed to meet the Directive 97/24/EC and their emission factors were reduced according to the factors given in the latest version of COPERT III.

Emissions from buses were scaled down according to the proportion running on ultra-low sulphur diesel fuel in each year, the proportion fitted with oxidation catalysts or particulate traps (CRTs) and the effectiveness of these measures in reducing emissions from the vehicles.

The older in-service vehicles in the test surveys that were manufactured to a particular emission standard would have covered a range of different ages. Therefore, an emission factor calculated for a particular emission standard (*e.g.* ECE 15.04) from the emission functions and coefficients from TRL and COPERT II is effectively an average value for vehicles of different ages which inherently takes account of possible degradation in emissions with vehicle age. However, for the more recent emission standards (Euro 1 and 2), the vehicles would have been fairly new when the emissions were measured. Therefore, based on data from the European Auto-Oil study, the deterioration in emissions with age or mileage was taken into account for catalyst cars. It was assumed that emissions of CO and NO_X increase by 60% over 80,000 km, while emissions of NMVOCs increase by 30% over the same mileage. Based on the average annual mileage of cars, 80,000 km corresponds to a time period of 6.15 years. Emissions from Euro 3 and 4 light-duty vehicles were assumed to degrade at rates described earlier, consideration given to the durability requirements of the Directive 98/69/EC.

For methane, factors for pre-Euro 1 and/or Euro 1 standards for each vehicle type were taken from COPERT III which provided either full speed-emission factor equations or single average factors for urban, rural and highway roads. Methane emission factors for other Euro standards were scaled according to the ratio in the THC emission factors between the corresponding Euro standards. This assumes that methane emissions are changed between each standard to the same extent as total hydrocarbons so that the methane fraction remains constant. Emission factors for nitrous oxide (N_2O) are the road-type factors taken from COPERT III. Due to lack of available data, no distinction between different Euro standards can be discerned, except for the higher N_2O emissions arising from petrol vehicles fitted with a three-way catalyst (Euro 1 onwards). Exhaust emissions of benzene and 1,3-butadiene are calculated by applying speciation mass fractions to the HC emission factors. Values of speciation fractions for different categories of vehicles and fuels were taken from COPERT III. Hot emission factors for CH_4 and N_2O were taken from estimates for European vehicles and emission control technologies published in the IPCC Revised 1996 Guidelines for National Greenhouse Gas Inventories. Fewer measurements have been made on emissions of these pollutants from vehicles. Therefore, only average emission factors are used, covering all vehicle speed or road types.

B4 Cold-start exhaust emissions

If the temperatures of engine and catalyst components are below those associated with normal operation, inefficiencies in combustion and catalytic conversion tend to result in elevated rates of fuel consumption and emissions. This is particularly true for petrol engines and the effect is even more severe for cars fitted with three-way catalysts, as the catalyst does not function properly until the catalyst is also warmed up. These elevated emissions, which are partly due to fuel enrichment and partly due to increased engine and transmission friction, are usually termed *cold-start emissions*, though in theory emission levels can be elevated even if component temperatures are only marginally lower than those leading to the optimal removal of pollutants, and thus cold-start emissions can actually occur after any start event. Emission factors have been derived for cars and LGVs from tests performed with the engine starting cold and warmed up. The difference between the two measurements can be regarded as an additional cold-start penalty, paid on each trip a vehicle is started with the engine (and catalyst) cold.

The procedure for estimating cold-start emissions is taken from COPERT II, taking account of the effects of ambient temperature on emission factors for different vehicle technologies and its effect on the distance travelled with the engine cold. A factor, the ratio of cold to hot emissions, is used and applied to the fraction of kilometres driven with cold engines to estimate the cold-start emissions from a particular vehicle type using the following formula:

$$E_{cold} = \beta \, . \, E_{hot} \, . \, (e^{cold}/e^{hot} - 1)$$

Where:

E_{hot}	=	hot exhaust emissions from the vehicle type
β	=	fraction of kilometres driven with cold engines
e^{cold}/e^{hot}	=	ratio of cold to hot emissions for the particular pollutant and vehicle type

The parameters β and e^{cold}/e^{hot} are both dependent on ambient temperature and β is also dependent on driving behaviour in, particular the average trip length, as this determines the time available for the engine and catalyst to warm up. The equations relating e^{cold}/e^{hot} to ambient temperature for each pollutant and vehicle type were taken from COPERT II and were used with an annual mean temperature for the UK of 11^{o}C. This is based on historic trends in Met Office data for ambient temperatures over different parts of the UK.
The factor β is related to ambient temperature and average trip length by the following equation taken from COPERT II:

$$\beta = 0.698 - 0.051 \, . \, l_{trip} - (0.01051 - 0.000770 \, . \, l_{trip}) \, . \, t_a$$

Where:

l_{trip}	=	average trip length
t_a	=	average temperature

An average trip length for the UK of 8.4 km was used, taken from Andre *et al.* (1993). This gives a value for β of 0.23.

This methodology is used to estimate annual UK cold-start emissions of NO_x, CO and NMVOCs from petrol and diesel cars and LGVs. Emissions were calculated separately for catalyst and non-catalyst petrol vehicles. Cold-start emissions data are not available for heavy-duty vehicles, but these are thought to be negligible (Boulter, 1996). All the cold-start emissions are assumed to apply to urban driving. Cold-start emissions data are not available for the pollutants methane and nitrous oxide.

B5 Evaporative emissions

Evaporative emissions of petrol fuel vapour from the tank and fuel delivery system in vehicles constitute a significant fraction of total NMVOC emissions from road transport. The procedure for estimating evaporative emissions of NMVOCs takes account of changes in ambient temperature and fuel volatility. There are three different mechanisms by which petrol fuel evaporates from vehicles:

(i) *Diurnal loss*. This arises from the increase in the volatility of the fuel and expansion of the vapour in the fuel tank due to the diurnal rise in ambient temperature. Evaporation through “tank breathing” will occur each day for all vehicles with petrol fuel in the tank, even when stationary.

(ii) *Hot soak loss.* This represents evaporation from the fuel delivery system when a hot engine is turned off and the vehicle is stationary. It arises from transfer of heat from the engine and hot exhaust to the fuel system, where fuel is no longer flowing.

(iii) *Running loss.* These are evaporative losses that occur while the vehicle is in motion.

Evaporative emissions are dependent on ambient temperature and the volatility of the fuel and, in the case of diurnal losses, on the daily *rise* in ambient temperature. Fuel volatility is usually expressed by the empirical fuel parameter known as Reid vapour pressure (RVP). For each of these mechanisms, equations relating evaporative emissions to ambient temperature and RVP were developed by analysis of empirically based formulae derived in a series of CONCAWE research studies in combination with UK measurements data reported by TRL. Separate equations were developed for vehicles with and without evaporative control systems fitted such as carbon canister devices. The overall methodology is similar to that reported by COPERT II, but the data are considered to be more UK-biased.

Evaporative emissions are calculated using monthly average temperature and RVP data. Using this information, evaporative emissions are calculated from the car fleet for each month of the year and the values summed to derive the annual emission rates. Calculating emissions on a monthly basis enables subtle differences in the seasonal fuel volatility trends and differences in monthly temperatures to be better accounted for. Monthly mean temperatures from 1970-2003 were used for the calculations based on Met Office for Central England (CET data). The monthly average, monthly average daily maximum and monthly average diurnal rise in temperatures were required. The monthly average RVP of petrol sold in the UK used historic trends data on RVP and information from UKPIA on the RVP of summer and winter blends of fuels supplied in recent years and their turnover patterns at filling stations. The average RVP of summer blends of petrol in the UK in 2003 was 68 kPa, 2kPa below the limit set by European Council Directive 98/70/EC for Member States with 'arctic' summer conditions.

All the equations for diurnal, hot soak and running loss evaporative emissions from vehicles with and without control systems fitted developed for the inventory are shown in Table B2. The inventory uses equations for Euro 1 cars with "first generation" canister technology, based on early measurements, but equations taken from COPERT III leading to lower emissions were used for Euro 2-4 cars as these better reflected the fact that modern cars must meet the 2 grammes per test limit on evaporative emissions by the diurnal loss and hot soak cycles under Directive 98/69/EC.

For diurnal losses, the equations for pre-Euro 1(non-canister) and Euro 1 cars were developed from data and formulae reported by CONCAWE (1987), Barlow (1993) and ACEA (1995). Equations for Euro 2-4 cars were taken from COPERT III. The equations specified in Table B2 give diurnal loss emissions in g/vehicle.day for uncontrolled ($DL_{uncontrolled}$) and Euro 1 and Euro 2-4 canister controlled vehicles (DL_{EU1}, $DL_{EUII-IV}$). Total annual diurnal losses were calculated from the equation:

$$E_{diurnal} = 365 \,.\, N \,.\, (DL_{uncontrolled} \,.\, F_{uncontrolled} + DL_{EU1} \,.\, F_{EUI} + DL_{EUII-IV} \,.\, F_{EUII-IV})$$

Where:

N	=	number of petrol vehicles (cars and LGVs) in the UK parc
$F_{uncontrolled}$	=	fraction of vehicles not fitted with carbon canisters, assumed to be the same as the fraction of pre-Euro 1 vehicles
F_{EUI}	=	fraction of Euro 1 vehicles in the fleet
$F_{EUII-IV}$	=	fraction of Euro 2-4 vehicles in the fleet

For hot soak losses, the equations were developed from data and formulae reported by CONCAWE (1990), Barlow (1993) and COPERT II. The equations specified in Table B2 give hot soak loss emissions in g/vehicle.trip for uncontrolled ($HS_{uncontrolled}$) and Euro 1 and Euro 2-4 canister controlled (HS_{EUI}, $HS_{EUII-IV}$) vehicles. Total annual hot soak losses were calculated from the equation:

$$E_{hot\ soak} = (VKM/\, l_{trip}) \,.\, (HS_{uncontrolled} \,.\, F_{uncontrolled} + HS_{EU1} \,.\, F_{EUI} + HS_{EUII-IV} \,.\, F_{EUII-IV})$$

Where:

VKM	=	total number of vehicle kilometres driven in the UK by the petrol vehicles (cars and LGVs)
l_{trip}	=	average trip length (8.4 km in the UK)

For running losses, the equations were developed from data and formulae reported by CONCAWE (1990) and COPERT II. The equations specified in Table B2 give running loss emissions in g/vehicle.km for uncontrolled ($RL_{uncontrolled}$) and canister controlled ($RL_{controlled}$) vehicles with no distinction made between Euro 1 and Euro 2-4 canister cars. Total annual running losses were calculated from the equation:

$$E_{running\ loss} = VKM.\, (RL_{uncontrolled} \,.\, F_{uncontrolled} + RL_{controlled} \,.\, F_{controlled})$$

Where:

$$F_{controlled} = F_{EUI} + F_{EUII-IV}$$

Table B2: Equations for diurnal, hot soak and running loss evaporative emissions from vehicles with and without control systems fitted

Emission factor	Units	Uncontrolled vehicle (pre-Euro 1)
Diurnal loss ($DL_{uncontrolled}$)	g/vehicle.day	$1.54 * (0.51*T_{rise} + 0.62*T_{max} + 0.22*RVP - 24.89)$
Hot soak ($HS_{uncontrolled}$)	g/vehicle.trip	$exp(-1.644 + 0.02*RVP + 0.0752*T_{mean})$
Running loss ($RL_{uncontrolled}$)	g/vehicle.km	$0.022 * exp(-5.967 + 0.04259*RVP + 0.1773*T_{mean})$

Emission factor	Units	Carbon canister controlled vehicle (Euro 1)
Diurnal loss (DL_{EUI})	g/vehicle.day	$0.3 * (DL_{uncontrolled})$
Hot soak (HS_{EUI})	g/vehicle.trip	$0.3 * exp(-2.41 + 0.02302*RVP + 0.09408*T_{mean})$
Running loss ($RL_{controlled}$)	g/vehicle.km	$0.1 * (RL_{uncontrolled})$

Emission factor	Units	Carbon canister controlled vehicle (Euro 2-4)
Diurnal loss ($DL_{EUII-IV}$)	g/vehicle.day	$0.2 * 9.1 * exp(0.0158*(RVP-61.2) + 0.0574*(T_{max}-T_{rise}-22.5) + 0.0614*(T_{rise}-11.7))$
Hot soak ($HS_{EUII-IV}$)	g/vehicle.trip	0
Running loss ($RL_{controlled}$)	g/vehicle.km	$0.1 * (RL_{uncontrolled})$

Where:

T_{rise} = diurnal rise in temperature in ^{o}C
T_{max} = maximum daily temperature in ^{o}C
T_{mean} = annual mean temperature in ^{o}C
RVP = Reid vapour pressure of petrol in kPa

C6 Tyre, brake and road surface wear emissions

PM emissions from tyre wear, brake wear and road surface wear calculated for the NAEI using the methodology presented in the European Environment Agency's Emission Inventory Guidebook. This method was developed jointly by TRL and the Laboratory of Applied Thermodynamics (LAT) of the Aristotle University of Thessaloniki.

C7 Resuspension

An emission factor for PM_{10} of 40 mg/vkm for all types of road and vehicle is quoted in the UK NAEI to aid the understanding of roadside pollution measurements, but resuspension is not included in official reported estimates to avoid double counting. Double counting could be an issue given that particles that are re-entrained in the air have already been emitted and deposited.

Appendix C: Definitions of *Art.Kinema* parameters

The following definitions of the parameters in Art.Kinema are taken from De Haan and Keller (2003). The definitions apply to a speed profile consisting of n data rows of time in seconds t_i ($1 <= i <= n$), and speed v_i in km h^{-1}, with ($1 <= i < n$).

Distance-related	Total distance	$dist = (t_2 - t_1)\frac{v_1}{3.6} + \sum_{i=2}^{n}(t_i - t_{i-1})\frac{v_i}{3.6}$
Time-related	Total time	$T_{total} = t_2 - t_1 + \sum_{i=2}^{n}(t_i - t_{i-1})$
	Driving time	$T_{drive} = T_{total} - T_{stop}$
	Cruise time	$T_{cruise} = T_{drive} - T_{acc} - T_{dec}$
	Drive time spent accelerating	$T_{acc} = \begin{cases} t_2 - t_1 & (a_1 > acc\_threshold) \\ 0 & (else) \end{cases} + \sum_{i=2}^{n} \begin{cases} t_i - t_{i-1} & (a_i > acc\_threshold) \\ 0 & (else) \end{cases}$
	Drive time spent decelerating	$T_{dec} = \begin{cases} t_2 - t_1 & (a_1 < -acc\_threshold) \\ 0 & (else) \end{cases} + \sum_{i=2}^{n} \begin{cases} t_i - t_{i-1} & (a_i < -acc\_threshold) \\ 0 & (else) \end{cases}$
	Time spent braking	$T_{brake} = \begin{cases} t_2 - t_1 & (a_1 < brake\_threshold) \\ 0 & (else) \end{cases} + \sum_{i=2}^{n} \begin{cases} t_i - t_{i-1} & (a_i < brake\_threshold) \\ 0 & (else) \end{cases}$
	Standing time	$T_{stop} = \begin{cases} t_2 - t_1 & (v_1 = 0 \wedge a_1 = 0) \\ 0 & (\text{else}) \end{cases} + \sum_{i=2}^{n} \begin{cases} t_i - t_{i-1} & (v_i = 0 \wedge a_i = 0) \\ 0 & (\text{else}) \end{cases}$
	% of time driving	$\%drive = \frac{T_{drive}}{T_{total}}$
	% of cruising	$\%cruise = \frac{T_{cruise}}{T_{total}}$
	% of time accelerating	$\%acc = \frac{T_{acc}}{T_{total}}$
	% of time decelerating	$\%dec = \frac{T_{dec}}{T_{total}}$
	% of time braking	$\%brake = \frac{T_{brake}}{T_{total}}$
	% of time standing	$\%stop = \frac{T_{stop}}{T_{total}}$
Speed - related	Average speed (trip)	$\bar{v}_{trip} = 3.6\frac{dist}{T_{total}}$
	Average driving speed	$\bar{v}_{drive} = 3.6\frac{dist}{T_{drive}}$

	Standard deviation of speed	$v\_sd = \sigma_v = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} v_i^{\ 2}}$ (i.e., v_sd corresponds to $\overline{v}_{trip}$, not $\overline{v}_{drive}$)
	Speed: 75th - 25th percentile	
	Maximum speed	
Acceleration -related	Average acceleration	$a\_av = \overline{a} = \frac{1}{T_{total}}\sum_{i=1}^{n} a_i$
	Average positive accel.	$a\_pos\_av = \overline{a}_{pos} = \left(\sum_{i=1}^{n}\begin{cases}1 & (a_i > 0)\\ 0 & (\text{else})\end{cases}\right)^{-1}\sum_{i=1}^{n}\begin{cases}a_i & (a_i > 0)\\ 0 & (\text{else})\end{cases}$
	Average negative accel.	$a\_neg\_av = \overline{a}_{neg} = \left(\sum_{i=1}^{n}\begin{cases}1 & (a_i < 0)\\ 0 & (\text{else})\end{cases}\right)^{-1}\sum_{i=1}^{n}\begin{cases}a_i & (a_i < 0)\\ 0 & (\text{else})\end{cases}$
	Standard deviation of accel.	$a\_sd = \sigma_a = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} a_i^{\ 2}}$
	Standard dev. of positive acceleration	$a\_pos\_sd = \sigma_{a\_av\_pos} = \sqrt{\frac{1}{n_{a\_pos}-1}\sum_{i=1}^{n}\begin{cases}a_i^2 & (a_i > 0)\\ 0 & (else)\end{cases}}$ where $n_{a\_pos} = \sum_{i=1}^{n}\begin{cases}1 & (a_i > 0)\\ 0 & (else)\end{cases}$
	Accel: 75th - 25th percentile	
	Number of accelerations	$acc\_nr = \sum_{i=1}^{n}\begin{cases}1 & (a_i > \text{acc\_threshold} \wedge a_{i-1} \le \text{acc\_threshold})\\ 0 & (\text{else})\end{cases}$
	Accelerations per km	$acc\_rate = 1000\frac{acc\_nr}{dist}$
Stop-related	Number of stops	$stop\_nr = \sum_{i=1}^{n}\begin{cases}1 & (\{v_i = 0 \wedge a_i = 0\} \wedge \{v_{i-1} \neq 0 \vee a_{i-1} \neq 0\})\\ 0 & (\text{else})\end{cases}$
	Stops per km	$stop\_rate = 1000\frac{stop\_nr}{dist}$
	Average stop duration	$stop\_T\_av = \overline{T}_{stop} = \frac{T_{stop}}{stop\_nr}$
	Average distance between stops	
Dynamics-related	Relative positive acceleration	$RPA = \frac{1}{dist}\sum_{i=1}^{n}\begin{cases}\frac{a_i v_i}{3.6} & (a_i > 0)\\ 0 & (\text{else})\end{cases}$
	Positive kinetic energy	$PKE = \frac{1}{dist}\sum_{i=2}^{n}\begin{cases}v_i^2 - v_{i-1}^2 & (v_i > v_{i-1})\\ & (else)\end{cases}$
	Relative positive speed Relative real speed	$\left.\right\}$ $\frac{\frac{1}{T}\int_0^T (v_i)dt}{\overline{v}} = \frac{\int_0^T (v_i)dt}{x}$

Relative square speed

Relative positive square speed (RPSS)

Relative real square speed

$$\frac{\frac{1}{T}\int_0^T (v_i)^2\,dt}{\bar{v}} = \frac{\int_0^T (v_i)^2\,dt}{x}$$

Relative cubic speed

Relative positive cubic speed

Relative real cubic speed

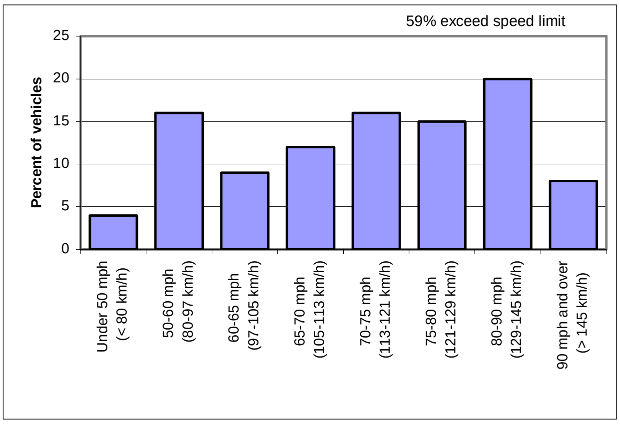
$$\frac{\frac{1}{T}\int_0^T (v_i)^3\,dt}{\bar{v}} = \frac{\int_0^T (v_i)^3\,dt}{x}$$

Root mean square of acceleration $\sqrt{\frac{1}{T}\int_0^T (a)^2\,dt}$

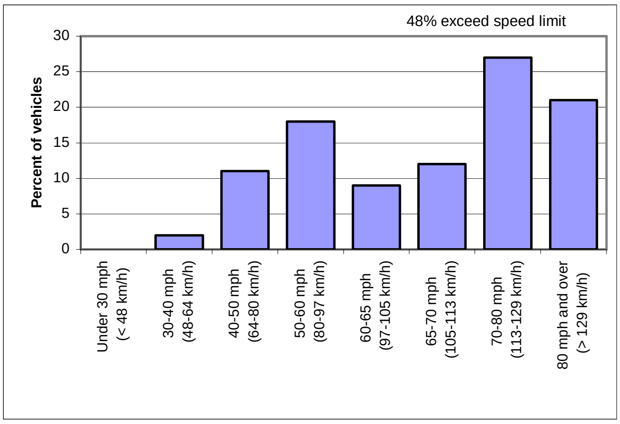
Appendix D: Vehicle speed distributions

Vehicle Speed distributions: Motorcycles

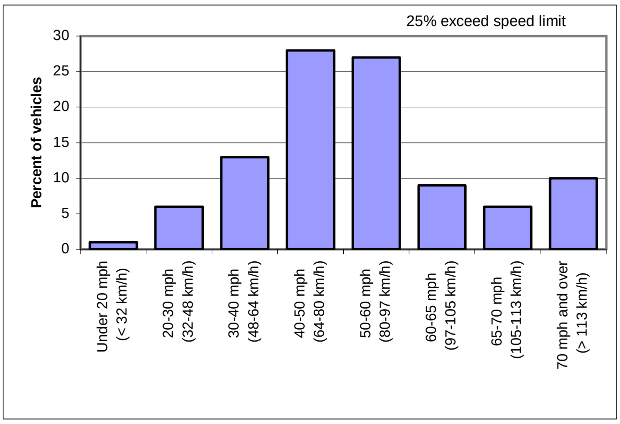
Non-urban roads: Motorways



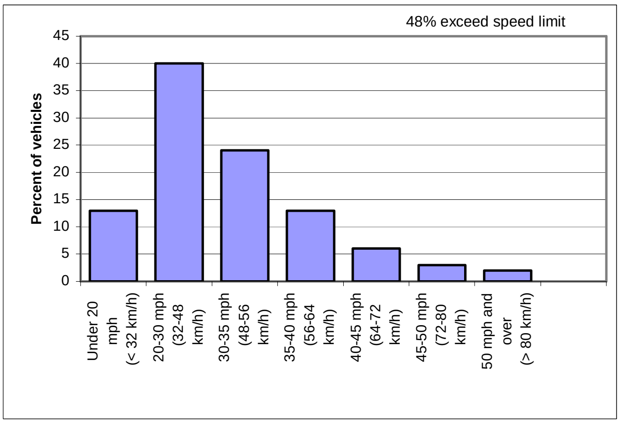
Non-urban roads: Dual carriageways



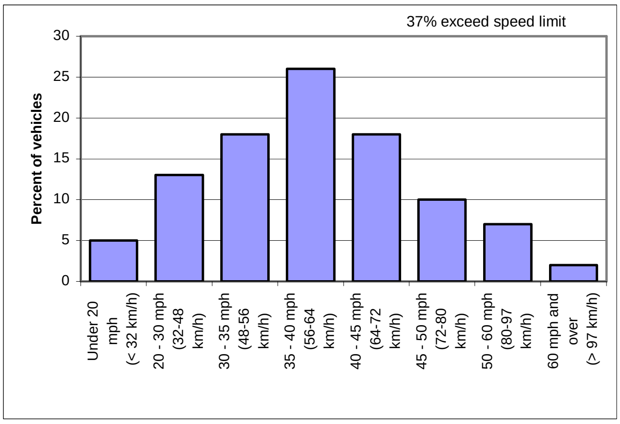
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads

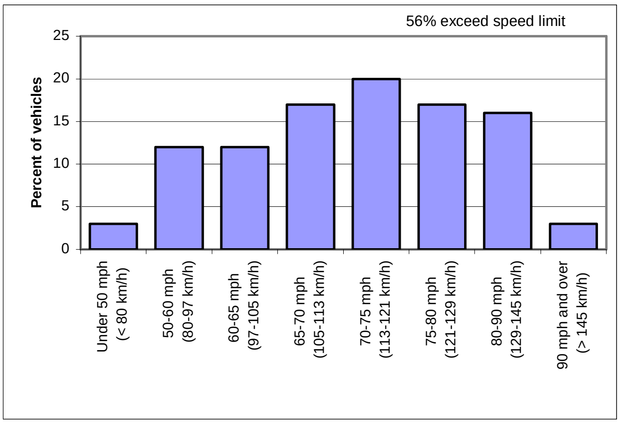


Urban roads: 40 mph speed limit roads

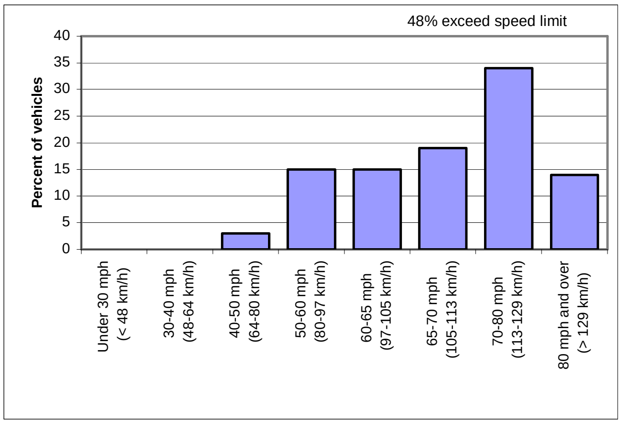


Vehicle Speed distributions: Cars

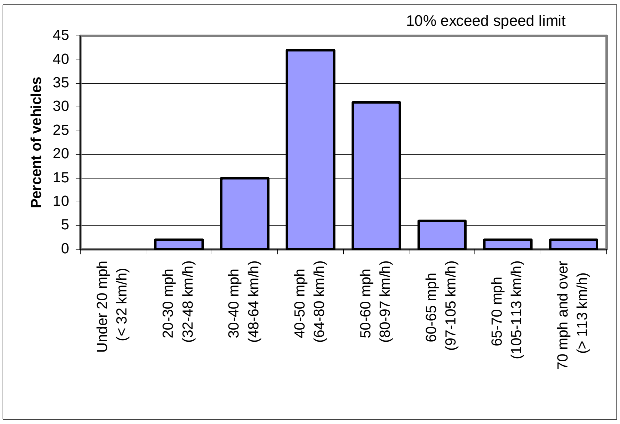
Non-urban roads: Motorways



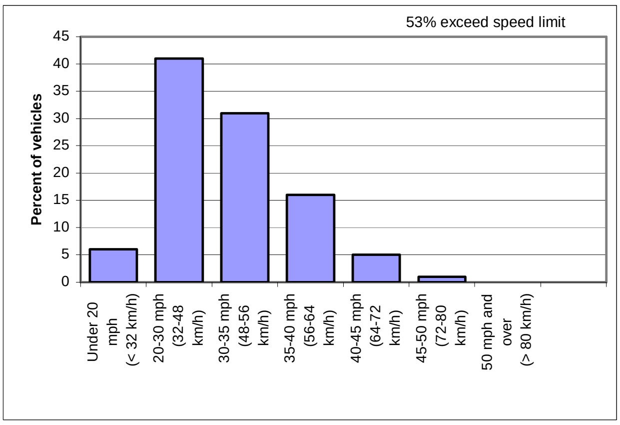
Non-urban roads: Dual carriageways



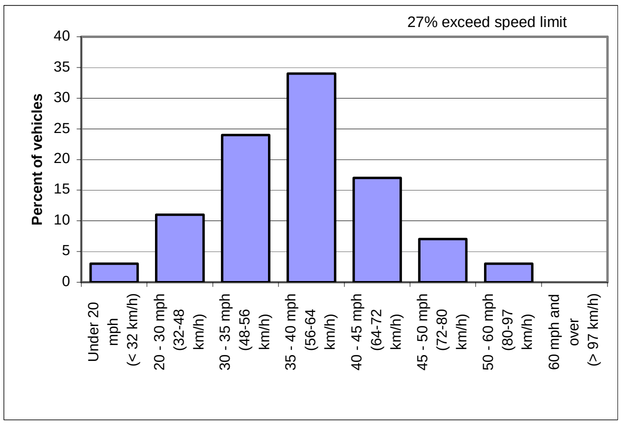
Non-urban roads: Single carriageways



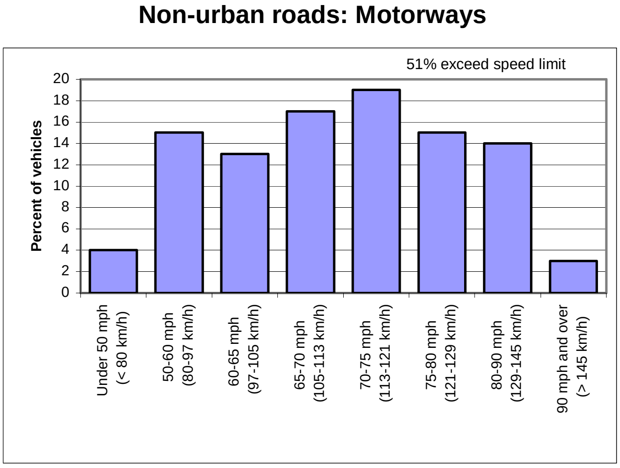
Urban roads: 30 mph speed limit roads

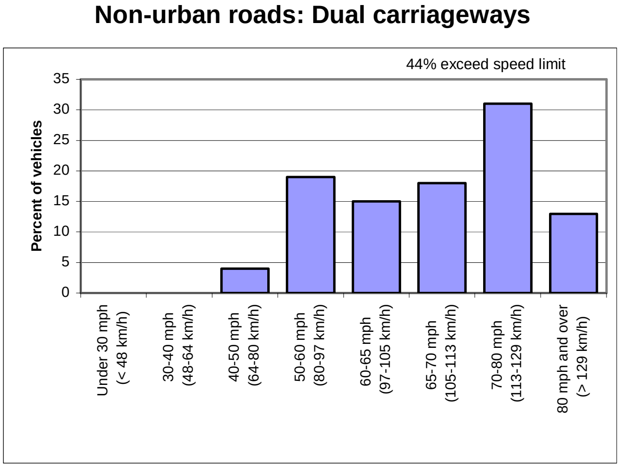


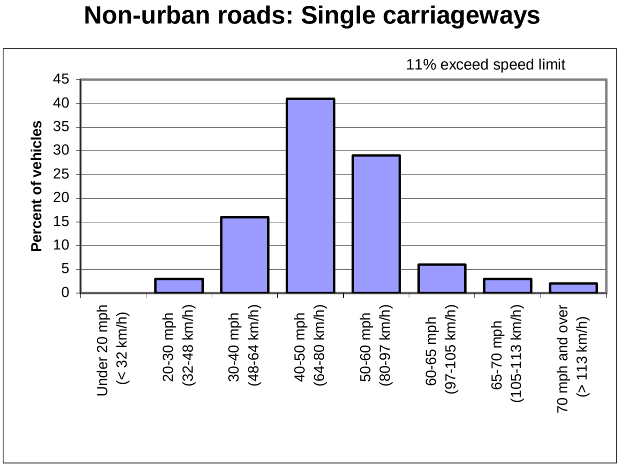
Urban roads: 40 mph speed limit roads

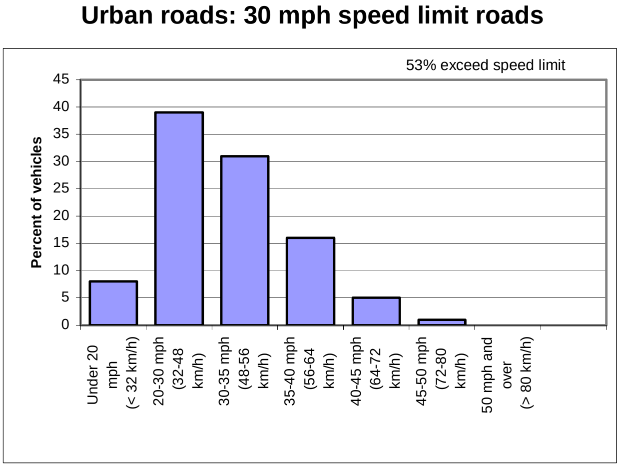


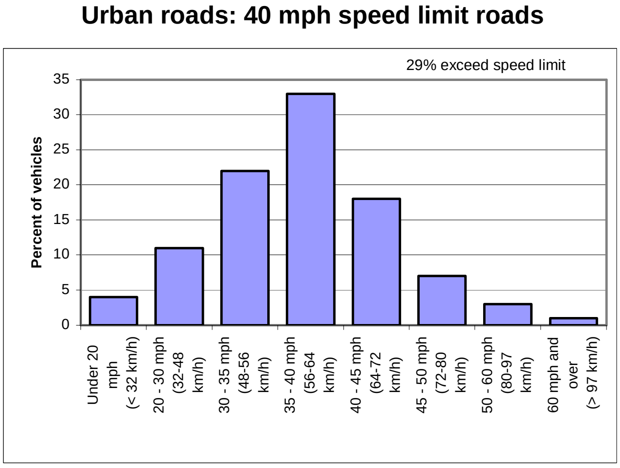
Vehicle Speed distributions: Light goods vehicles





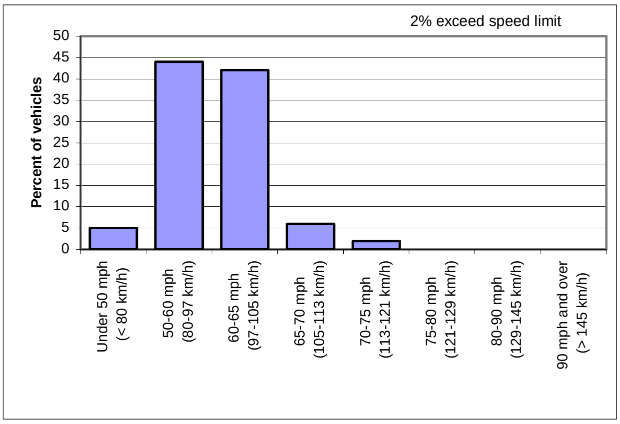




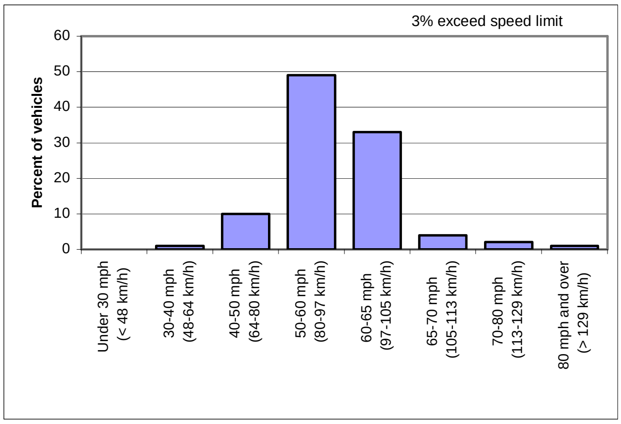


Vehicle Speed distributions: Buses and coaches

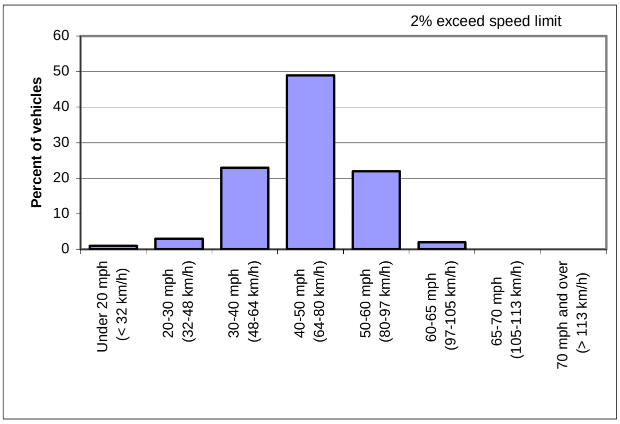
Non-urban roads: Motorways



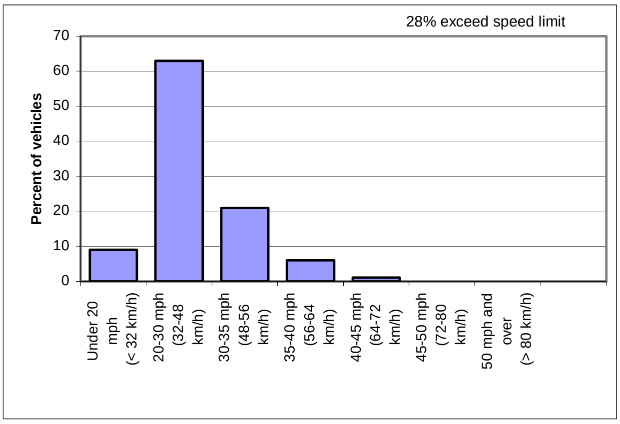
Non-urban roads: Dual carriageways



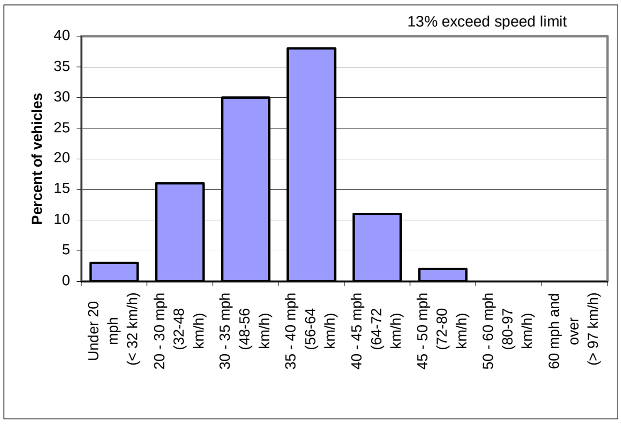
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads

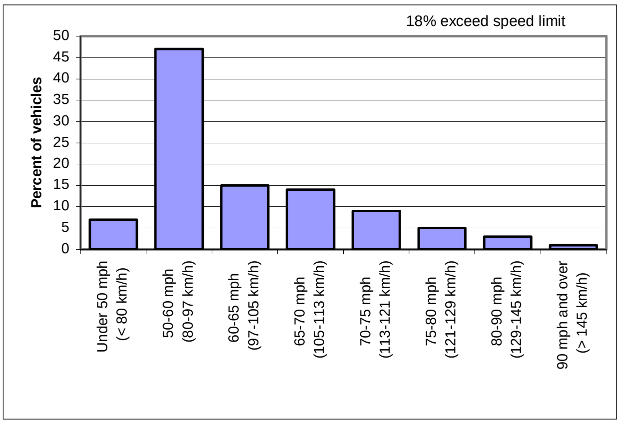


Urban roads: 40 mph speed limit roads

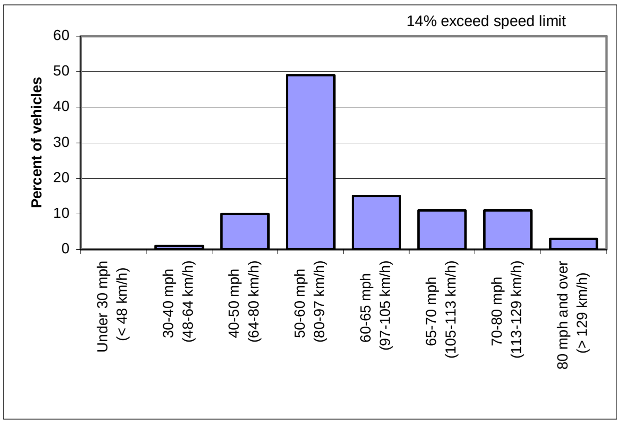


Vehicle Speed distributions: Rigid HGV – 2-axle

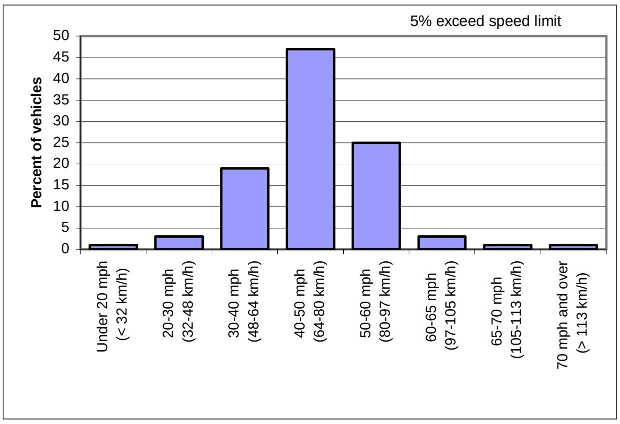
Non-urban roads: Motorways



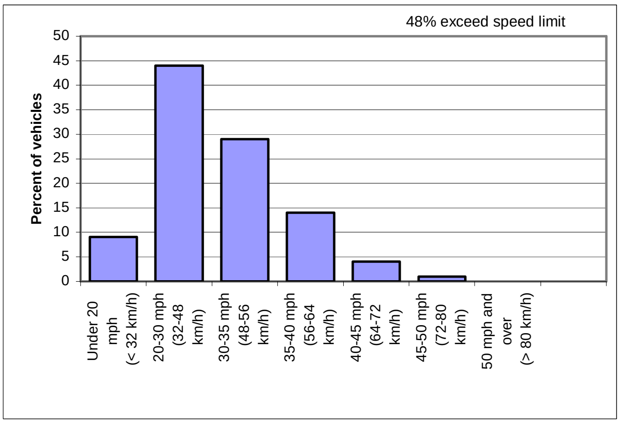
Non-urban roads: Dual carriageways



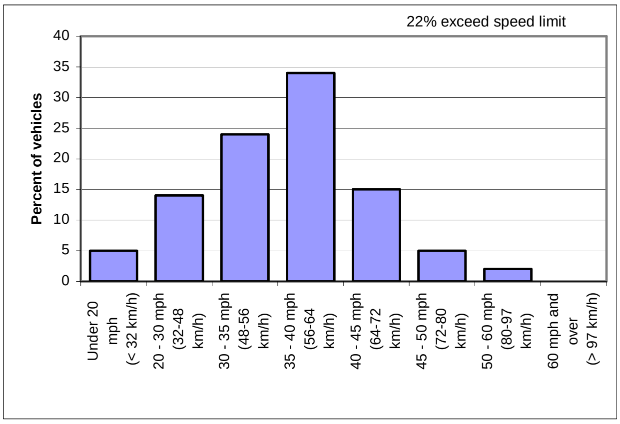
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads

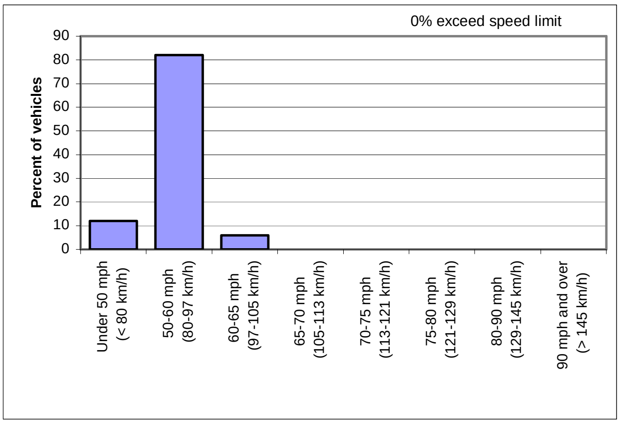


Urban roads: 40 mph speed limit roads

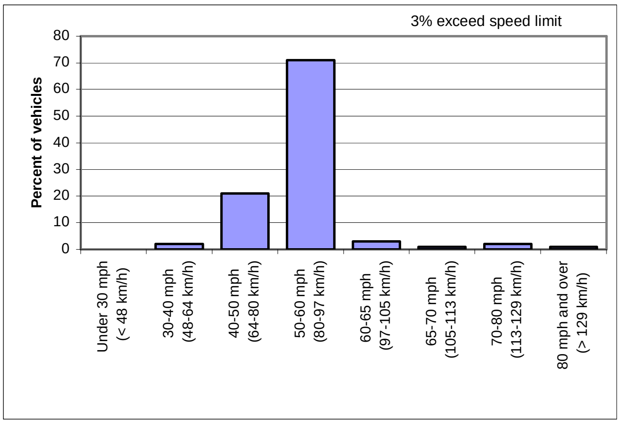


Vehicle Speed distributions: Rigid HGV – 3-axle

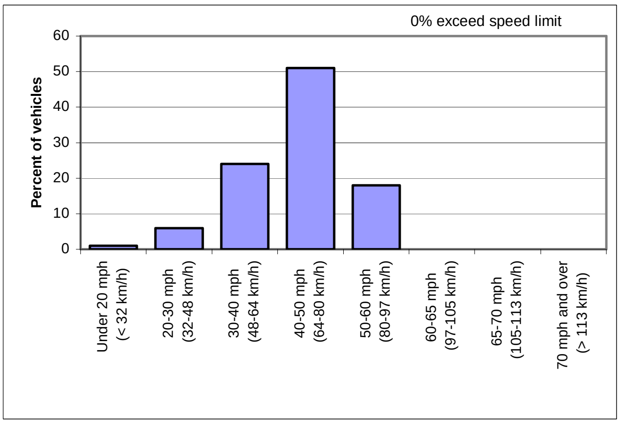
Non-urban roads: Motorways



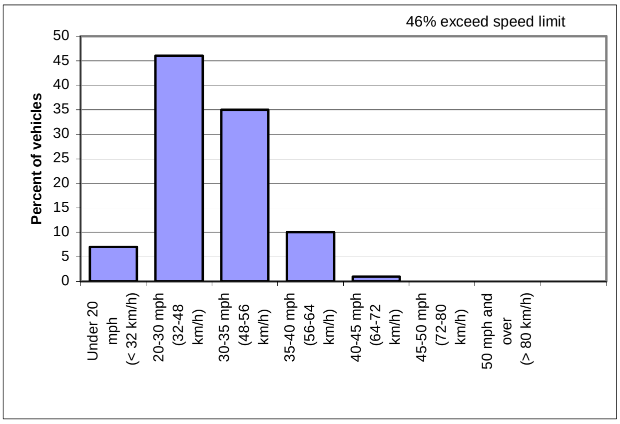
Non-urban roads: Dual carriageways



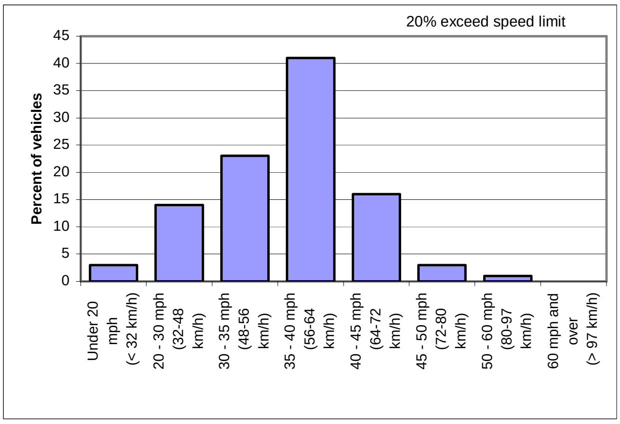
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads

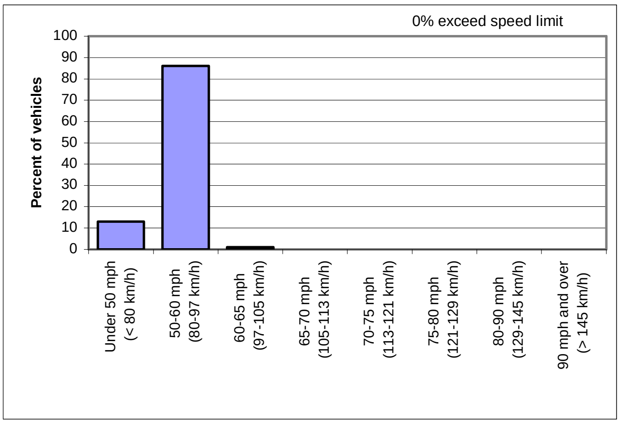


Urban roads: 40 mph speed limit roads

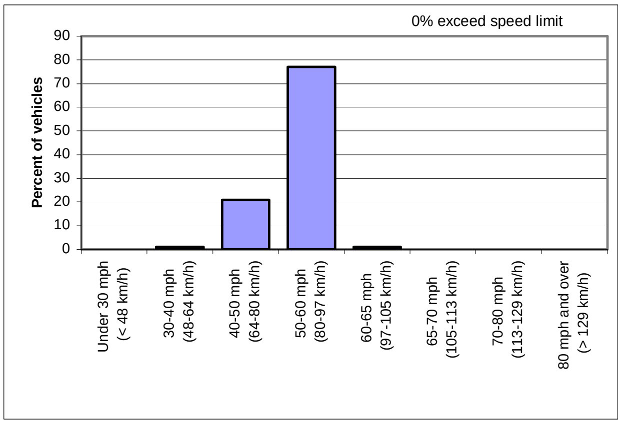


Vehicle Speed distributions: Rigid HGV – 4-axle

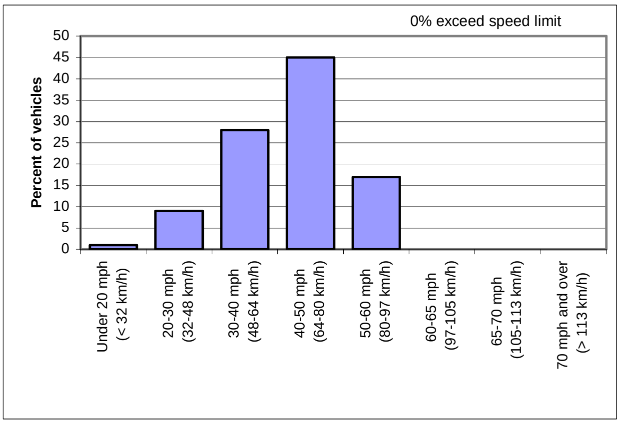
Non-urban roads: Motorways



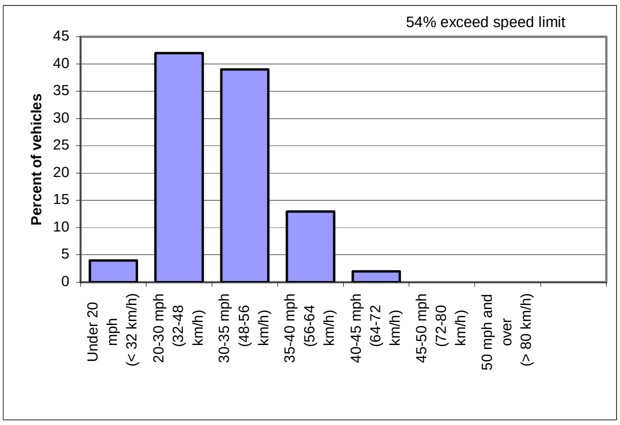
Non-urban roads: Dual carriageways



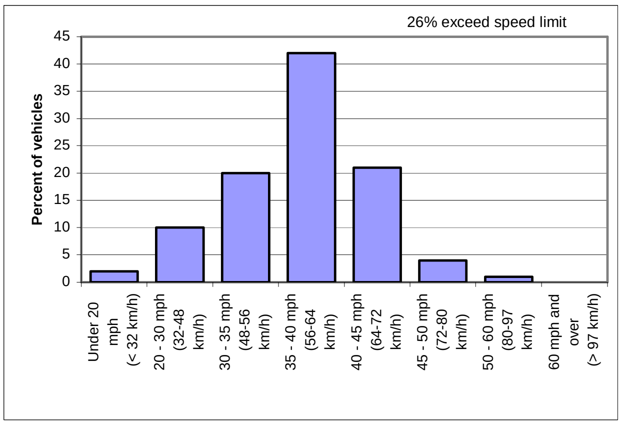
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads

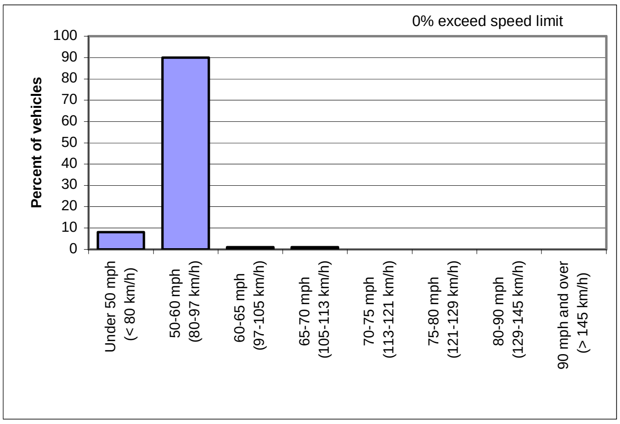


Urban roads: 40 mph speed limit roads

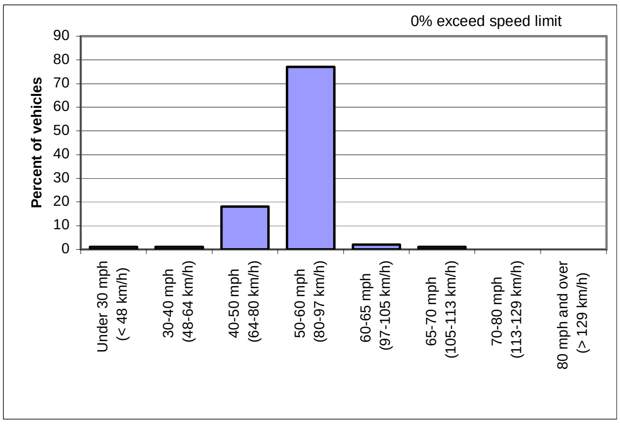


Vehicle Speed distributions: Articulated HGV – 4-axle

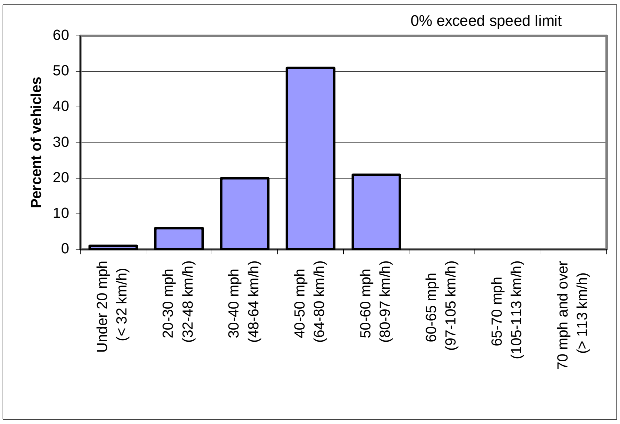
Non-urban roads: Motorways



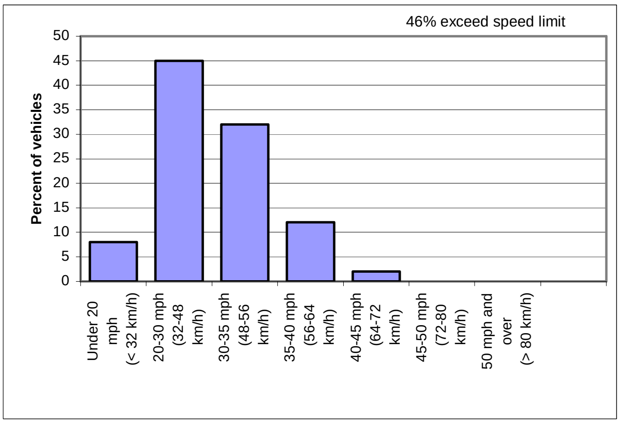
Non-urban roads: Dual carriageways



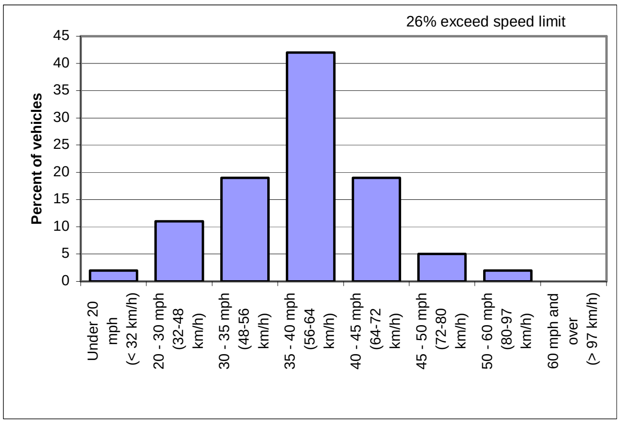
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads

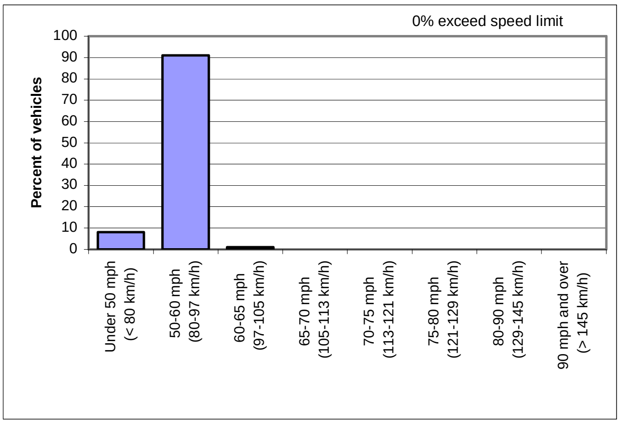


Urban roads: 40 mph speed limit roads

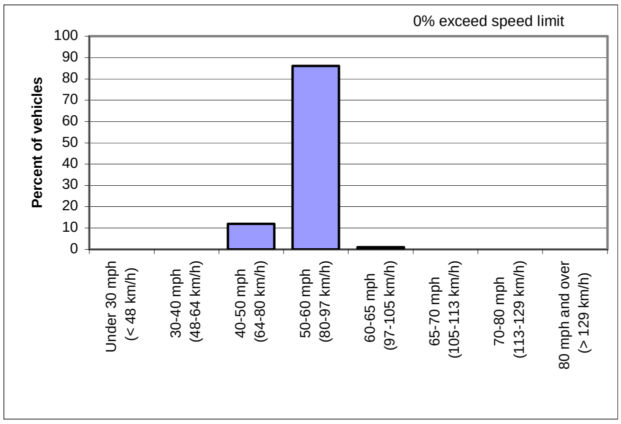


Vehicle Speed distributions: Articulated HGV – 5-axle or greater

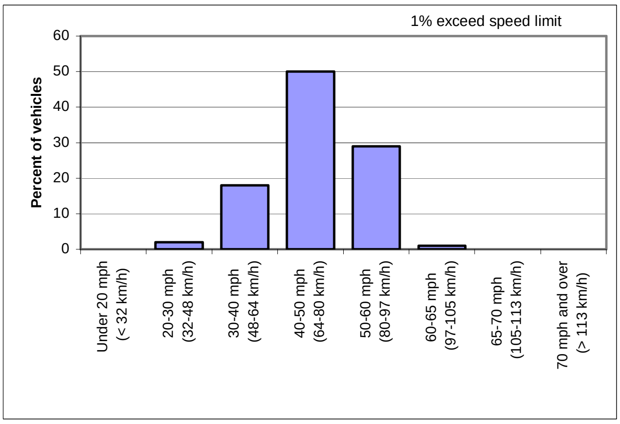
Non-urban roads: Motorways



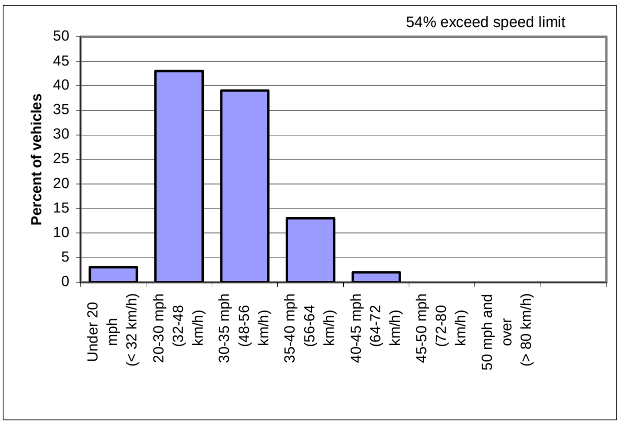
Non-urban roads: Dual carriageways



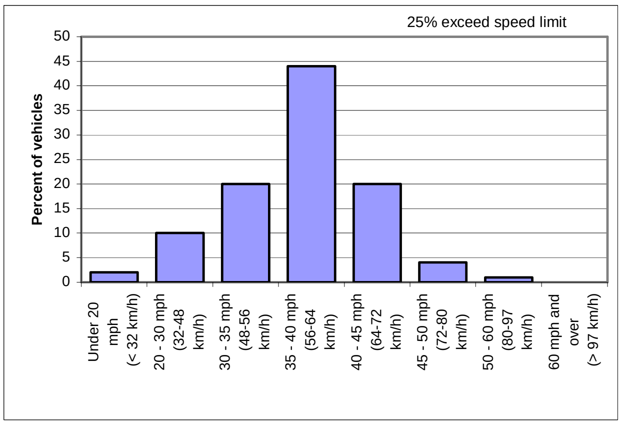
Non-urban roads: Single carriageways



Urban roads: 30 mph speed limit roads



Urban roads: 40 mph speed limit roads



Appendix E: Average *Art.Kinema* parameters

The following tables list the average *Art.Kinema* parameters for cars, LGVs, HGVs and buses per set of cycles. It should be noted that some of the driving cycles has been analysed both as a complete cycles and as its individual sub-cycles, so some double counting may occur for these cycles. However, the cycles have been used in this manner (overall and individually) in deriving previous emission functions and could therefore be considered to be different cycles.

Table E1. Average *Art.Kinema* parameters for: Cars		**Ref Book driving cycles**	**UKEFD cycles**	**WSL cycles**	**ARTEMIS driving cycles**	**Real world driving patterns**
	Number of cycles	160	45	6	16	3964
Parameter	**Units**	**Average**	**Average**	**Average**	**Average**	**Average**
total distance	m	12928.1	9211.8	6746.0	18864.1	14499.1
total time	s	979.4	622.9	644.8	1244.3	1145.8
driving time	s	863.2	558.8	557.2	1100.4	1032.2
drive time	s	264.0	191.6	181.7	276.9	263.2
drive time spent accelerating	s	312.0	194.0	191.7	435.6	400.7
drive time spent decelerating	s	288.0	174.0	184.5	389.0	368.7
time spent braking	s	195.1	119.7	111.0	289.8	230.8
standing time	s	116.2	64.1	87.7	143.9	113.6
% of time driving	-	86.7%	88.3%	92.0%	86.7%	91.8%
% of cruising	-	26.1%	31.5%	39.0%	20.8%	24.0%
% of time accelerating	-	31.6%	29.8%	26.9%	34.8%	35.5%
% of time decelerating	-	29.1%	27.2%	26.1%	31.2%	32.3%
% of time braking	-	20.5%	19.5%	13.7%	23.6%	19.6%
% of time standing	-	13.3%	11.7%	8.0%	13.3%	8.2%
average speed (trip)	km/h	43.3	48.1	56.5	50.9	50.7
average driving speed	km/h	47.2	51.1	57.8	55.1	53.9
standard dev. of speed	km/h	18.2	15.7	9.9	25.1	20.6
75th - 25th percentile	km/h	30.6	26.1	16.3	40.4	32.7
maximum speed	km/h	80.2	77.2	77.9	100.1	92.1
average acceleration	m/s^2	0.002	0.001	0.002	0.000	0.001
average pos. acc.	m/s^2	0.464	0.455	0.314	0.487	0.410
average neg. acc.	m/s^2	-0.497	-0.480	-0.321	-0.537	-0.448
standard dev. of acc.	m/s^2	0.584	0.548	0.438	0.658	0.583
standard dev. of positive acc.	m/s^2	0.362	0.335	0.287	0.407	0.380
standard dev. of negative acc.	m/s^2	0.419	0.388	0.350	0.496	0.473
75th - 25th percentile	m/s^2	0.411	0.388	0.316	0.495	0.424
number of accelerations	-	52.96	31.04	37.00	81.63	76.90
nr. of acc. per km	/km	8.92	9.89	9.57	7.03	6.10
number of stops	-	8.43	5.16	8.17	10.25	7.11
stops per km	/km	2.56	2.63	2.99	1.45	0.65
average stop duration#	s	12.57	10.87	7.27	11.79	14.33
average distance between stops#	m	3912.8	3868.3	3529.4	3786.7	4562.5
Relative Positive Acceleration	m/s^2	0.186	0.180	0.137	0.201	0.164
Positive Kinetic Energy	m/s^2	0.347	0.334	0.254	0.373	0.304
Cumulative Squared Positive Kinetic Energy	m^2/s^4	4.888	4.795	2.992	5.941	4.711
Relative Positive Speed	-	0.456	0.435	0.446	0.481	0.467
Relative Real Speed	-	0.774	0.784	0.851	0.748	0.808
Relative Square Speed	m/s	15.603	16.201	17.190	18.715	17.726
Relative Positive Square Speed	m/s	7.024	6.744	7.288	8.783	7.987
Relative Real Square Speed	m/s	12.925	13.764	15.659	15.066	14.934
Relative Cubic Speed	m^2/s^2	332.7	359.4	394.1	468.5	378.3
Relative Positive Cubic Speed	m^2/s^2	148.8	147.8	162.5	215.6	165.3
Relative Real Cubic Speed	m^2/s^2	288.0	320.1	370.8	395.5	327.8
Root Mean Square of Acceleration	m/s^2	0.200	0.195	0.159	0.199	0.168

- Average of only the cycles that have stops within them

Table E2. Average *Art.Kinema* parameters for: LGVs

Parameter	Units	Ref Book driving cycles	UKEFD cycles	WSL cycles	Real world driving patterns
Number of cycles		32	26	6	367
		Average	Average	Average	Average
total distance	m	8512.5	9858.6	6746.0	11110.0
total time	s	811.5	666.2	644.8	1559.6
driving time	s	719.1	615.0	557.2	1303.4
drive time	s	203.8	285.6	181.7	448.7
drive time spent accelerating	s	280.5	174.3	191.7	464.7
drive time spent decelerating	s	235.4	155.7	184.5	390.2
time spent braking	s	163.0	99.6	111.0	302.4
standing time	s	92.4	51.2	87.7	256.2
% of time driving	-	87.3%	93.7%	92.0%	86.7%
% of cruising	-	23.1%	46.5%	39.0%	30.4%
% of time accelerating	-	34.9%	24.8%	26.9%	30.8%
% of time decelerating	-	29.3%	22.5%	26.1%	25.5%
% of time braking	-	21.0%	14.1%	13.7%	19.7%
% of time standing	-	12.7%	6.3%	8.0%	13.3%
average speed (trip)	km/h	35.5	60.4	56.5	27.4
average driving speed	km/h	39.0	62.3	57.8	31.1
standard dev. of speed	km/h	18.0	15.3	9.9	14.9
75th - 25th percentile	km/h	29.3	21.9	16.3	26.9
maximum speed	km/h	70.3	84.6	77.9	63.1
average acceleration	m/s^2	0.000	0.001	0.002	-0.001
average pos. acc.	m/s^2	0.428	0.355	0.314	0.399
average neg. acc.	m/s^2	-0.500	-0.379	-0.321	-0.479
standard dev. of acc.	m/s^2	0.590	0.404	0.438	0.544
standard dev. of positive acc.	m/s^2	0.336	0.246	0.287	0.320
standard dev. of negative acc.	m/s^2	0.455	0.303	0.350	0.448
75th - 25th percentile	m/s^2	0.433	0.248	0.316	0.381
number of accelerations	-	49.66	25.88	37.00	93.19
nr. of acc. per km	/km	8.81	4.38	9.57	14.05
number of stops	-	7.44	4.38	8.17	13.23
stops per km	/km	1.85	1.20	2.99	7.15
average stop duration#	s	10.77	8.16	7.27	18.46
average distance between stops#	m	2121.8	6633.6	3529.4	1759.4
Relative Positive Acceleration	m/s^2	0.187	0.113	0.137	0.159
Positive Kinetic Energy	m/s^2	0.350	0.217	0.254	0.292
Cumulative Squared Positive Kinetic Energy	m^2/s^4	4.110	2.771	2.992	2.575
Relative Positive Speed	-	0.499	0.392	0.446	0.465
Relative Real Speed	-	0.780	0.864	0.851	0.801
Relative Square Speed	m/s	13.345	18.927	17.190	10.784
Relative Positive Square Speed	m/s	6.419	7.120	7.288	4.944
Relative Real Square Speed	m/s	10.954	17.181	15.659	8.825
Relative Cubic Speed	m^2/s^2	240.7	440.3	394.1	130.8
Relative Positive Cubic Speed	m^2/s^2	110.6	164.0	162.5	58.8
Relative Real Cubic Speed	m^2/s^2	205.9	409.6	370.8	108.9
Root Mean Square of Acceleration	m/s^2	0.201	0.123	0.159	0.188

- Average of only the cycles that have stops within them

Table E3: Average *Art.Kinema* parameters: HGVs		**Ref Book driving cycles**	**UKEFD cycles**	**FiGE cycles**	**Real world driving patterns**
Number of cycles		25	12	4	426
Parameter	**Units**	**Average**	**Average**	**Average**	**Average**
total distance	m	8059.6	8968.2	14747.0	21658.4
total time	s	963.6	892.1	900.0	1826.2
driving time	s	813.9	725.5	899.0	1665.0
drive time	s	321.5	339.5	517.0	718.6
drive time spent accelerating	s	266.2	214.0	212.5	502.7
drive time spent decelerating	s	226.6	172.3	169.5	444.0
time spent braking	s	144.9	120.7	78.0	248.5
standing time	s	149.6	166.6	1.0	161.1
% of time driving	-	84.7%	80.7%	99.9%	92.4%
% of cruising	-	34.6%	39.3%	57.4%	38.3%
% of time accelerating	-	27.0%	22.7%	23.6%	28.7%
% of time decelerating	-	23.1%	18.7%	18.8%	25.4%
% of time braking	-	14.8%	13.0%	8.7%	14.7%
% of time standing	-	15.3%	19.3%	0.1%	7.6%
average speed (trip)	km/h	30.6	36.6	59.0	41.7
average driving speed	km/h	33.8	39.3	59.1	43.7
standard dev. of speed	km/h	14.3	13.3	15.8	15.4
75th - 25th percentile	km/h	23.4	19.9	20.9	20.9
maximum speed	km/h	59.3	58.9	79.7	62.0
average acceleration	m/s^2	-0.001	0.000	0.000	0.000
average pos. acc.	m/s^2	0.312	0.373	0.172	0.300
average neg. acc.	m/s^2	-0.370	-0.456	-0.202	-0.330
standard dev. of acc.	m/s^2	0.388	0.430	0.335	0.412
standard dev. of positive acc.	m/s^2	0.216	0.213	0.163	0.291
standard dev. of negative acc.	m/s^2	0.295	0.334	0.347	0.372
75th - 25th percentile	m/s^2	0.249	0.247	0.222	0.256
number of accelerations	-	39.20	27.42	32.75	132.23
nr. of acc. per km	/km	8.46	9.07	2.84	11.59
number of stops	-	6.92	7.42	0.50	8.36
stops per km	/km	3.31	5.96	0.03	0.92
average stop duration#	s	19.13	25.15	2.00	15.58
average distance between stops#	m	2984.7	5262.3	21784.3	7331.9
Relative Positive Acceleration	m/s^2	0.114	0.123	0.077	0.114
Positive Kinetic Energy	m/s^2	0.218	0.238	0.144	0.186
Cumulative Squared Positive Kinetic Energy	m^2/s^4	1.442	1.643	1.150	1.332
Relative Positive Speed	-	0.438	0.389	0.497	0.406
Relative Real Speed	-	0.842	0.839	0.926	0.853
Relative Square Speed	m/s	11.442	12.575	18.108	13.844
Relative Positive Square Speed	m/s	4.784	4.786	8.746	4.753
Relative Real Square Speed	m/s	10.141	11.342	17.285	12.575
Relative Cubic Speed	m^2/s^2	174.1	219.1	371.1	252.3
Relative Positive Cubic Speed	m^2/s^2	68.3	80.4	176.4	75.2
Relative Real Cubic Speed	m^2/s^2	160.1	205.7	359.6	237.7
Root Mean Square of Acceleration	m/s^2	0.148	0.175	0.092	0.143

- Average of only the cycles that have stops within them

Table E4: Average *Art.Kinema* parameters: Buses		**Ref Book driving cycles**	**UKEFD cycles**	**FiGE cycles**	**Real world driving patterns**
Number of cycles		22	4	4	225
Parameter	**Units**	**Average**	**Average**	**Average**	**Average**
total distance	m	6411.6	14747.0	14747.0	10439.1
total time	s	1058.8	900.0	900.0	1765.3
driving time	s	895.3	899.0	899.0	1501.5
drive time	s	272.4	517.0	517.0	305.5
drive time spent accelerating	s	345.5	212.5	212.5	608.4
drive time spent decelerating	s	277.8	169.5	169.5	587.7
time spent braking	s	203.5	78.0	78.0	430.1
standing time	s	163.5	1.0	1.0	263.7
% of time driving	-	85.1%	99.9%	99.9%	87.3%
% of cruising	-	26.9%	57.4%	57.4%	17.0%
% of time accelerating	-	32.3%	23.6%	23.6%	35.8%
% of time decelerating	-	26.0%	18.8%	18.8%	34.5%
% of time braking	-	18.9%	8.7%	8.7%	25.1%
% of time standing	-	14.9%	0.1%	0.1%	12.7%
average speed (trip)	km/h	23.4	59.0	59.0	22.4
average driving speed	km/h	26.8	59.1	59.1	25.4
standard dev. of speed	km/h	13.2	15.8	15.8	12.4
75th - 25th percentile	km/h	22.0	20.9	20.9	23.6
maximum speed	km/h	51.4	79.7	79.7	49.8
average acceleration	m/s^2	0.000	0.000	0.000	0.000
average pos. acc.	m/s^2	0.440	0.172	0.172	0.445
average neg. acc.	m/s^2	-0.682	-0.202	-0.202	-0.458
standard dev. of acc.	m/s^2	0.584	0.335	0.335	0.520
standard dev. of positive acc.	m/s^2	0.308	0.163	0.163	0.318
standard dev. of negative acc.	m/s^2	0.411	0.347	0.347	0.352
75th - 25th percentile	m/s^2	0.379	0.222	0.222	0.503
number of accelerations	-	39.09	32.75	32.75	160.65
nr. of acc. per km	/km	7.69	2.84	2.84	24.37
number of stops	-	14.95	0.50	0.50	17.17
stops per km	/km	3.03	0.03	0.03	14.59
average stop duration#	s	11.36	2.00	2.00	17.05
average distance between stops#	m	947.3	21784.3	21784.3	1295.7
Relative Positive Acceleration	m/s^2	0.176	0.077	0.077	0.170
Positive Kinetic Energy	m/s^2	0.334	0.144	0.144	0.259
Cumulative Squared Positive Kinetic Energy	m^2/s^4	2.785	1.150	1.150	1.835
Relative Positive Speed	-	0.494	0.497	0.497	0.423
Relative Real Speed	-	0.800	0.926	0.926	0.736
Relative Square Speed	m/s	9.398	18.108	18.108	8.849
Relative Positive Square Speed	m/s	4.325	8.746	8.746	3.695
Relative Real Square Speed	m/s	7.902	17.285	17.285	6.681
Relative Cubic Speed	m^2/s^2	112.9	371.1	371.1	87.8
Relative Positive Cubic Speed	m^2/s^2	45.9	176.4	176.4	36.3
Relative Real Cubic Speed	m^2/s^2	99.3	359.6	359.6	67.5
Root Mean Square of Acceleration	m/s^2	0.227	0.092	0.092	0.200

- Average of only the cycles that have stops within them

Appendix F: ARTEMIS correction factors

Gear-shift behaviour

It was observed in ARTEMIS that the gear-shift strategy affects CO_2 emissions by between 2*%* and 15*%*. For other pollutants the effects are smaller. The correction factor (*CF*) is used for CO_2 according to the formula:

$$CF = \frac{emission\,CO_2(Artemis\ strategy)}{emission\,CO_2(other\ strategy)} \quad \text{(Equation F1)}$$

For all driving cycles other than the NEDC, CF is equal to one. For the NEDC, the values of CF for the ARTEMIS rural and motorway cycles are 1.08 and 1.03 respectively.

Emission degradation

The influence of the mileage M_1 or M_2 [km] is expressed by the formula:

$$\frac{emission(M_1)}{emission(M_2)} = \frac{y(M_1)}{y(M_2)} \quad \text{(Equation F2)}$$

Values of ***y*** are given for Euro 1 and 2 petrol cars in Table F1, and for Euro 3 and 4 petrol cars in Table F2, in both cases for urban and rural situations, *i.e.* for an average speed lower than 19 km h^{-1} and higher than 63 km h^{-1} respectively. For an intermediate speed ***V***, the following formula has to be used:

$$y(V) = y(urban) + \frac{(V-19)\cdot(y(rural)-y(urban))}{44} \quad \text{(Equation F3)}$$

Table F1: Emission degradation correction factor *y* = *a* x *mileage* + *b*, for Euro 1 and Euro 2 petrol vehicles. Mileage expressed in km, y normalised for the corresponding average mileage.

Petrol Euro 1 and 2		Capacity class (l)	Average mileage (km)	*a*	*b*	Value at 100,000 km
y (urban) for V≤19 km h^{-1} (urban situation)	CO	≤1.4	29,057	1.523E-05	0.557	2.1
		1.4-2.0	39,837	1.148E-05	0.543	1.7
		>2.0	47,028	9.243E-06	0.565	1.5
	HC	≤1.4	29,057	1.215E-05	0.647	1.9
		1.4-2.0	39,837	1.232E-05	0.509	1.7
		>2.0	47,028	1.208E-05	0.432	1.6
	NO_x	All	44,931	1.598E-05	0.282	1.9
y (rural) for V≥63 km h^{-1} (rural situation)	CO	≤1.4	29,057	1.689E-05	0.509	2.2
		1.4-2.0	39,837	9.607E-06	0.617	1.6
		>2.0	47,028	2.704E-06	0.873	1.1
	HC	≤1.4	29,057	6.570E-06	0.809	1.5
		1.4-2.0	39,837	9.815E-06	0.609	1.6
		>2.0	47,028	6.224E-06	0.707	1.3
	NO_x	all	47,186	1.220E-05	0.424	1.6

Table F2: Emission degradation correction factor for Euro 3 and Euro 4 petrol vehicles.
y = *a* x *mileage* + *b*. Mileage expressed in km, *y* normalised for the corresponding average mileage.

Petrol Euro 3 and 4		Capacity class (l)	Average mileage (km)	***a***	***b***	Value at 100,000 km
y (urban) for V≤19 km h^{-1} (urban situation)	CO	≤1.4	32,407	7.129E-06	0.769	1.5
		>1.4	16,993	2.670E-06	0.955	1.2
	HC	≤1.4	31,972	3.419E-06	0.891	1.2
		>1.4	17,913	0	1	1.0
	NO_x	≤1.4	31,313	0	1	1.0
		>1.4	16,993	3.986E-06	0.932	1.3
y (rural) for V≥63 km h^{-1} (rural situation)	CO	≤1.4	30,123	1.502E-06	0.955	1.1
		>1.4	26,150	0	1	1.0
	HC	all	28,042	0	1	1.0
	NO_x	all	26,150	0	1	1.0

Ambient temperature

The hot emissions decrease with increasing temperature for petrol and petrol cars, but mainly for diesel cars. Between 10° and 20°C, the CO and HC emissions varies by 15-20%, the NO_x and CO_2 emissions by 2%, and PM is constant. It is therefore recommended to measure the emissions close to the country's average ambient temperature rather than at 'standard' temperature, especially where there is a large difference between the two.

The influence of the temperature T_1 or T_2 (°C) is expressed by the formulae

$$\frac{emission(T_1)}{emission(T_2)} = \frac{y(T_1)}{y(T_2)} \qquad \text{(Equation F4)}$$

Values of ***y*** are given for urban, rural and motorway driving behaviour in Table ~F3.

Table F3: Temperature correction factors for urban, rural or motorway driving behaviour
y = a * Temperature + b, or y = a e$^{(b\ *\ Temperature)}$ when in italics. Temperature in °C, y normalised at 23°C.

Pollutant	Fuel	Emission category	Urban		Rural		Motorway	
			a	***b***	***a***	***b***	***a***	***b***
CO	petrol	Pre-Euro 1	0.0021	0.95	0.003	0.93	0.0054	0.88
		Euro 2	-0.0115	1.3	0.002	0.95	-	-
		Euro 3	-0.0087	1.2	0.0053	0.88	-0.0008	1.02
		Euro 4	No correction		0.017	0.61	-	-
	diesel	Euro 2	-0.034	1.784	-0.075	2.72	-0.024	1.56
HC	petrol	Pre-Euro 1	-0.001	1.02	-0.0027	1.066	No correction	
		Euro 2	-0.016	1.37	No correction		-	-
		Euro 3	-0.0525	2.21	-0.025	1.57	-0.001	1.02
		Euro 4	*3.4627*	*-0.0544*	0.0107	0.7442	-	-
	diesel	Euro 2	-0.027	1.62	-0.032	1.75	*1.43*	*-0.015*
NOx	petrol	Pre-Euro 1	-0.0075	1.17	-0.0063	1.14	-0.0035	1.08
		Euro 2	-0.0091	1.21	0.0045	0.895	-	-
		Euro 3	-0.0084	1.19	-0.0027	1.065	-0.002	1.05
		Euro 4	-0.01	1.23	0.0013	0.97	-	-
	diesel	Euro 2	-0.0015	1.05	-0.0015	1.05	-0.0006	1.016
CO_2	petrol	Pre-Euro 1	-0.0038	1.09	-0.0038	1.09	-0.0033	1.08
		Euro 2	-0.0013	1.03	-0.0017	1.04	-	-
		Euro 3	-0.001	1.03	-0.0013	1.03	-0.0015	1.0342
		Euro 4	-0.0028	1.0619	-0.0016	1.0334	-	-
	diesel	Euro 2	-0.0015	1.03	-0.0017	1.04	-0.0009	1.0205
PM	diesel	Euro 2	0.005	0.88	No correction		-0.005	1.11

Ambient humidity

From the low to the high regulatory limit of humidity (*i.e.* 5.5 and 12.2 gH_2O/kg dry air) NO_x emissions decrease for the petrol and diesel vehicles by 30% and 15% respectively. This influence of the humidity is different from the legislative correction factor kH. Again it is therefore recommended when possible to perform the tests with an ambient air humidity close to the real-world average. The influence of the humidity on NO_x emission is expressed by the formula:

$$\frac{emission(H_1)}{emission(H_2)} = \frac{y(H_1)}{y(H_2)} \qquad \text{(Equation F5)}$$

Values of ***y*** are available for some vehicle classes and for urban and rural driving behaviour in Table F4. It is recommended to use the rural figures for motorway driving behaviour, and to use the petrol Euro 2 figures for petrol Pre-Euro 1 and Euro 1, petrol Euro 3 figures for petrol Euro 4, and diesel Euro 2 figures for the other diesel cases. For other pollutants, no correction factors are proposed.

Table F4: Correction factor for NO_x emissions corrected or not using the current method, for urban or rural driving behaviour. y = a * Humidity + b. Humidity in gH_2O/kg dry air, y normalised at 10.71 gH_2O/kg dry air.

	Fuel	Emission category	urban		rural	
			a	***b***	***a***	***b***
Uncorrected emissions	petrol	Euro 2	-0.052	1.5592	-0.0293	1.31
		Euro 3	-0.081	1.8669	-0.0284	1.3
	diesel	Euro 2	-0.0249	1.2668	-0.0307	1.325
Corrected emissions	petrol	Euro 2	-0.0182	1.1944	0.004	0.9571
		Euro 3	-0.0529	1.5654	-0.0093	1.0996
	diesel	Euro 2	0.0067	0.9281	0.0106	0.8869

Dilution ratio

The dilution ratio (between exhaust air and dilution air), the quality of the dilution air and the PM filter preconditioning did not seem to have a clear influence on the emissions. This could be due to the low sample size and to the widely standardised sampling and analysing conditions, respected by the participating laboratories. Nevertheless, the pollutant analysing and sampling conditions seem to be an important source of error, compared with the other parameters studied above. A correction factor could be determined for PM, but it is not applicable to the common ARTEMIS emission data, as the dilution ratio is usually unknown.

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