Published Project Report
PPR357

Creating the future of transport

Emission factors 2009: Report 4 – a review of methodologies for modelling cold-start emissions

P G Boulter and S Latham

TRL Limited

PUBLISHED PROJECT REPORT PPR357

Emission factors 2009: Report 4 - a review of methodologies for modelling cold-start emissions

Version: 4

By P G Boulter and S Latham

Prepared for:	**Department for Transport, Cleaner Fuels & Vehicles 4**
	Chris Parkin

This report has been prepared for the Department for Transport. The views expressed are those of the authors and not necessarily those of the Department for Transport.

If this report has been received in hard copy from TRL then, in support of the company's environmental goals, it will have been printed on paper that is FSC (Forest Stewardship Council) registered and TCF (Totally Chlorine-Free) registered.

	Approvals
Project Manager	*T Barlow*
Quality Reviewed	*I McCrae*

When purchased in hard copy, this publication is printed on paper that is FSC (Forest Stewardship Council) registered and TCF (Totally Chlorine Free) registered.

Contents

Page

Executive Summary

This Report presents a review of models for estimating cold-start exhaust emissions, with a view to updating the method contained within the UK National Atmospheric Emissions Inventory (NAEI).

Exhaust emissions of regulated pollutants are higher during the cold-start phase than when the engine, catalyst, drive train and tyres are at their design temperatures. This is due to a combination of incomplete fuel combustion in the engine, catalyst inefficiency, and increased friction in the engine and drive train and at the tyre-road interface.

A wide range of factors affect cold-start emissions, and the Report includes a brief summary of a number of studies dealing with the subject.

The method used in the NAEI for estimating cold-start emissions is summarised, and potential limitations are highlighted. The Report also identifies a number of potential sources of data which might be used to update and refine the modelling approach in the NAEI. In particular, several models are described, including COPERT, MEET, ARTEMIS and PHEM.

The ARTEMIS cold-start models for passenger cars represent the state-of-the-art at the present time. The models take into account average speed, ambient temperature, travelled distance and parking duration, as well as other parameters, and can be applied at different geographic scales. However, discussions relating to the implementation of the ARTEMIS cold-start model in national inventories are still in progress. Furthermore, the ARTEMIS cold start models are used to actually *generate* emission factors based on country-specific input data, and the collection of data for this purpose has not yet been conducted for the UK.

The main conclusion of the Report is that - before any more detailed modelling of cold-start emissions is attempted - the current NAEI model (which is based upon COPERT II) ought to be updated to reflect the COPERT 4 methodology. However, the compilers of COPERT are currently improving the methodology for cold-start emissions. In addition, a revised cold-start model for the Handbook of Emission Factors ought to be available in 2009. When these are published they should be considered for inclusion in the NAEI.

Consequently, new emission factors for the most recent car and LGV categories, and for heavy-duty vehicles, are not provided in the Report. For motorcycles, on the other hand, cold-start emission factors have been determined in the ARTEMIS project, and these are available for use in the NAEI.

1 Introduction

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

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

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

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

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

This Report presents the findings of Task 4, the overall aims of which were to review models for estimating cold-start exhaust emissions and to provide recommendations for the NAEI. A wide range of factors affect cold-start emissions, and Chapter 2 includes a brief review of a number of studies dealing with the subject. Models for estimating cold-start emissions are reviewed in Chapter 3, and the specific method used in the NAEI for estimating cold-start emissions is described in Chapter 4. Potential limitations of the NAEI method are highlighted. Chapter 6 provides the summary and recommendations of the work.

In the measurement and modelling of vehicle emissions, various abbreviations and terms are often used to describe the concepts and activities involved. Appendix A provides a list of abbreviations and a glossary which explains how specific terms are used in the context of this series of Reports. Full descriptions of the various modelling approaches (COPERT, MEET, ARTEMIS and PHEM) are then given in Appendices B to E, respectively.

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] 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.

2 Cold-start emissions

2.1 Background

If a vehicle has not been used for several hours, the temperatures of its engine and exhaust system will normally be similar to that of the ambient air. Once the engine is started and a journey begins, the temperatures of the engine and exhaust system gradually increase until they become comparatively stable at their normal operational levels. 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. Rates of emission and fuel consumption are higher during the warm-up phase than during thermally stable operation, particularly in the case of petrol-engined vehicles. There are a number of reasons for this, including the following:

- *Incomplete combustion*. When a petrol engine is running efficiently around its normal operational temperature and under low load, there is a near-stoichiometric balance in the combustion chamber between the fuel and the oxygen in the air. Ideally, the fuel vapour would use up all the oxygen during complete combustion to form carbon dioxide (CO_2) and water vapour. However, during the warm-up phase a fraction of the fuel will condense on cold surfaces within the inlet manifold and cylinder, thus reducing the amount available for combustion. Until the engine has warmed sufficiently, excess fuel must be delivered to compensate for the loss, to avoid misfire and to maintain driveability. This causes the engine to run rich (the air:fuel ratio in the cylinder decreases) and emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) rise accordingly.
- *Catalyst inefficiency*. For petrol cars equipped with a three-way catalyst, the performance of the catalyst is reduced. A three-way catalyst promotes three reactions: (i) the reduction of nitrogen oxides to nitrogen and oxygen, (ii) the oxidation of CO to CO_2 and (iii) the oxidation of unburnt HC to CO_2 and water. These three reactions occur most efficiently when the catalyst receives exhaust from an engine running at the stoichiometric point (14.7 parts oxygen to 1 part fuel, by weight). The exhaust gas composition is strongly dependent on the combustion mixture in the engine, and until the engine is sufficiently warm that it no longer needs an excess of fuel in the mixture, the air in the exhaust will lack sufficient oxidising agents to convert the HC and CO to water and CO_2. Furthermore, the catalytic converter is heated by the exhaust gases from the engine, and needs to reach a minimum ‘light-off’ temperature of around 300^{o}C in order to function adequately; below this temperature removal of pollutants is minimal.
- *Increased friction*. Fuel consumption is higher during the warm-up phase as a result of increased viscous friction due to the low lubricant temperatures in the engine and transmission, and increased rolling friction in the tyres.

The emissions produced during the warm-up phase are often called ‘cold-start’ emissions[4]. The use of the word ‘cold’ here is rather confusing. 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 engine start. It is also been suggested by Latham *et al*. (2000) that even after the catalyst has warmed up, prolonged low speed or low load operations (such as idling) could cause the catalyst temperature to drop below the optimum operating level, although this is not normally considered to constitute cold-start operation. In some modern vehicles the catalyst is placed nearer to the engine exhaust manifold (‘close coupling’) in order to minimise the possibility of this happening and to reduce the overall cold start effects.

For some pollutants a large proportion of the total road transport emission, especially in urban areas, is due to vehicles being driven under cold-start conditions. For example, according to the NAEI[5] 770 kt of CO were emitted as a result of cold starts in the UK during 2003, equating to 49% of total emissions from road transport. Most of the cold-start emissions would have occurred in urban areas, and for comparison ‘hot’ emissions of CO on urban roads in 2003 totalled 340 kt. For NO_x, on the other hand, only 10% of UK emissions from road transport in 2003 were due to cold starts.

[4] Wherever a general reference is made in this Report to ‘cold-start emissions’, this can be taken to mean ‘cold- start emissions and fuel consumption’, unless otherwise stated.
[5] http://www.naei.org.uk/data_warehouse.php

2.2 Factors affecting cold-start emissions

A wide range of factors affect cold-start emissions. Some fundamental factors include the following:

- The definition of the cold-start emission.
- The pollutant.
- The vehicle type (*e.g.* car, light goods vehicle, heavy goods vehicle).
- The fuel type (*e.g.* petrol, diesel).
- The level of vehicle technology, which is generally stated in terms of compliance with emission legislation (*e.g.* pre-Euro 1/I, Euro 1/I, Euro 2/II, *etc.*), and the engine management strategy.
- The engine and catalyst temperatures at the start and end of each journey. Not all journeys begin with the engine and catalyst at the ambient temperature and end with them at their full operational temperatures. The engine and catalyst temperatures - and/or their rates of change - are dependent on factors such as:
  - The ambient temperature
  - The wind speed
  - The parking duration
  - The driving cycle during the cold-start period.

Some of these parameters are discussed briefly in the following Sections.

2.2.1 The definition of the cold-start emission

Figure 1 shows an idealised representation of the instantaneous emission rate of a given pollutant as a function of time following an engine start (t=0). Under real-world driving conditions, the emission profile is much more variable than the one shown in Figure 1. The emission units and time units in this example are arbitrary, as the actual values are dependent upon multiple factors. The emission profile can be divided into an initial transient phase - during which the emission rate is initially high but decreases as the temperatures of the engine and catalyst increase - followed by a stable phase when the normal operational temperatures have been reached. The duration of the first (cold-start) phase is signified by t_{cold}, and the emission rate during thermally stable operation is given by E_{hot}. Area A represents the total hot emission during the cold-start period (E_{hot} x t), and area B represents the total cold-start excess emission during the same period. The total emission during the cold-start period is therefore given by A+B.

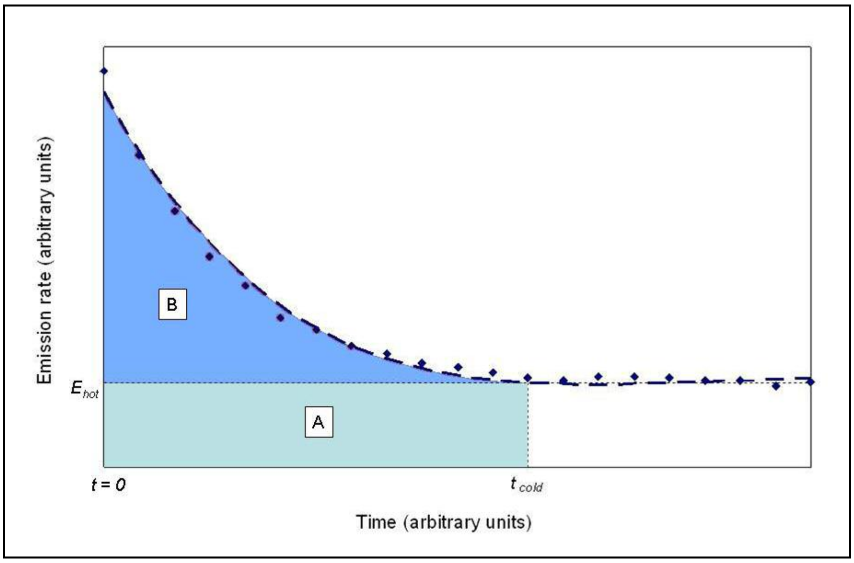

Figure 1: Schematic representation of emission rate as a function of time following an engine start (adapted from André and Joumard (2005)).

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

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

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

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

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

The methodology used to determine cold-start emissions has a major influence on the results (Weilenmann *et al.*, 2005). Cold-start emission factors have traditionally been determined via the collection of bag samples of the exhaust gas from vehicles operated on a chassis dynamometer from hot and cold starts under otherwise identical test conditions (including the same driving cycle)[6]. Most commonly, either the hot-start emissions have then been subtracted from the cold-start emissions to give an 'absolute excess' cold-start emission in grammes (equivalent to B in Figure 1), or a 'relative' cold-start emission factor over the full distance of the cycle (B/A) has been calculated. These terms are used in this Review, and where the text refers to cold-start emissions, the terms 'absolute excess' and 'relative' are used in this context, unless otherwise stated. In the case of the relative cold-start emission, if the driving cycle length does not exactly match the cold-start distance, then the quotient will be either underestimated or overestimated. It is likely that this will occur for almost all tests, and therefore the absolute cold-start emission value ought to be used where possible.

As an alternative, a short sub-cycle can be repeated several times. The overall duration of the driving cycle must be such that at least the last two sub-cycles are driven with a hot stabilised engine. The cold-start extra emissions can then be derived from the difference between the emissions measured during the sub-cycles when the engine is warming up, and the emissions measured over the same number of sub-cycles when the engine is hot (Weilenmann, 2001; Weilenmann *et al.*, 2005). According to Weilenmann *et al.* (2005), any test to generate cold-start emission factors ought to be based on repeated 'real-world' driving cycles (*i.e.* the driving cycles are derived from studies of real-world traffic and are statistically representative). However, some cycles (such as the FTP-75 and ECE legislative cycles) are not fully repetitive in this sense, and therefore a regression modelling approach has been applied to estimate cold-start emissions (*e.g.* Heeb *et al.* 2001; Weilenmann, 2001). Figure 2 shows cumulative CO emissions (solid line) during a driving cycle (dashed line). The thermally stable phase is approximated by the straight line. The intercept of this line on the *x*-axis gives the cold-start emission. Using this methodology it is possible to calculate cold-start emissions using measurements over non-repetitive cycles. In particular, the FTP-75 and ECE legislative cycles, for which a large number of measurements exist, can be used (Weilenmann, 2001).

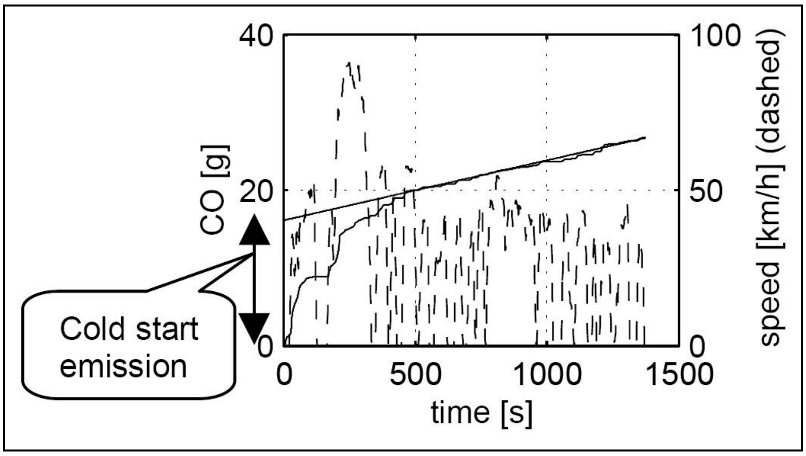

Figure 2: Cumulative CO emissions over a driving cycle, and definition of cold-start emission (Weilenmann, 2001).

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

2.2.2 The pollutant and the vehicle category

A review of the factors affecting cold-start emissions for various pollutants and vehicle types was undertaken by Boulter (1997). As the study was completed in 1997, the data relate to older vehicles which now represent a relatively small fraction of the current UK fleet. For petrol cars, the study found that absolute cold-start emissions of CO and HC were usually higher from non-catalyst vehicles (pre-Euro 1) than those from catalyst-equipped vehicles (Euro 1). However, the relative cold-start emissions of CO and HC were much higher for catalyst cars, mainly as a consequence of the very low emission rates during hot operation. NO_x emissions from non-catalyst petrol cars were found to be similar to those during hot operation. For catalyst-equipped cars, NO_x emissions tended to be slightly higher during the cold-start period. For diesel cars, the relative cold-start emission factors of CO and HC were found to be slightly lower than those for non-catalyst petrol cars. However, in absolute terms, diesel cars produced much lower cold-start emissions. NO_x emissions were found to be similar to those during hot operation. More recently, Weilenmann (2001) found that the cold-start emissions of HC and CO were significantly lower for Euro 2 cars than for Euro 1 cars, although NO_x emissions were comparable.

At type approval, emissions from light-duty vehicles are measured over the ‘New European Driving Cycle’ (NEDC). 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. This means that cold-start emissions are now fully included in the type approval test. Relative few cold start measurements exist for Euro 3 and Euro 4 vehicles, but an indication of the relative emission levels associated with different legislative classes can be obtained from the model developed in the ARTEMIS project (see Section 3.2.6 and Appendix D). Some examples are given for an ambient temperature of 20^{o}C and an average speed of 20 km/h in Figures 3 to 6 (adapted from André and Joumard (2005)).

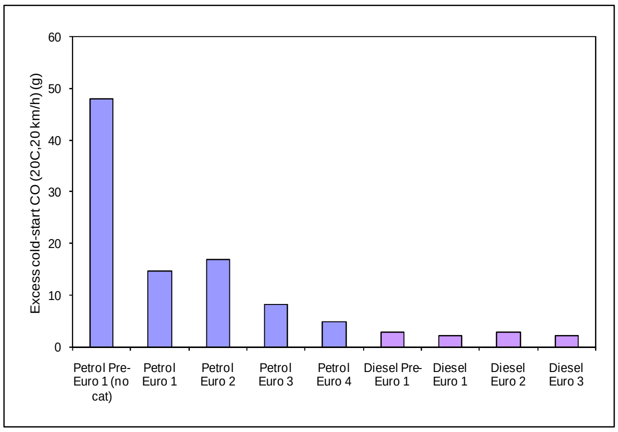

Figure 3: Excess CO emissions for an ambient temperature of 20^{o}C and an average speed of 20 km/h.

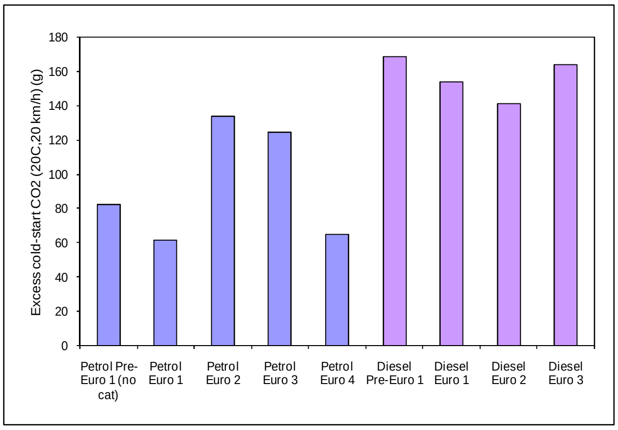

Figure 4: Excess CO_2 emissions for an ambient temperature of 20^{o}C and an average speed of 20 km/h.

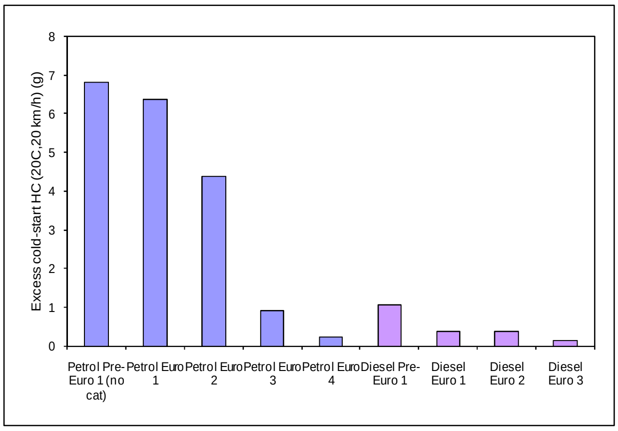

Figure 5: Excess HC emissions for an ambient temperature of 20°C and an average speed of 20 km/h.

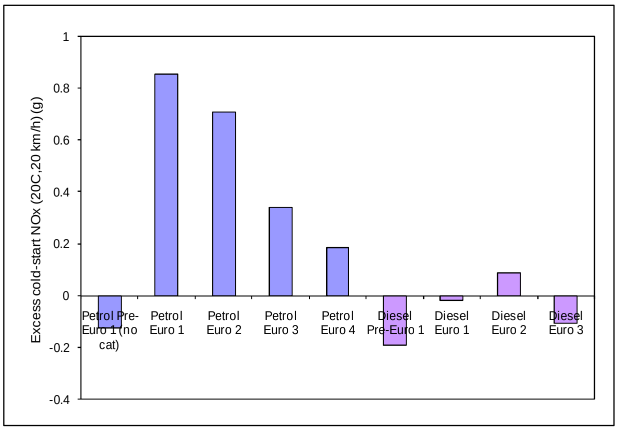

Figure 6: Excess NO_x emissions for an ambient temperature of 20°C and an average speed of 20 km/h.

Compared with passenger cars relatively little work has been conducted on cold-start emissions from heavy-duty diesel vehicles (HDVs). Boulter (1997) noted that excess cold-start emissions per HDV were minimal. However, although the total contribution of HDV extra emissions due to engine warm up may be small, local contributions to air pollution could be significant. Cold-start emissions from two Euro II HDVs were measured over real-world urban driving cycles by Engler *et al.* (2003). The measurements showed significant increases in energy consumption and emissions compared with thermally stable operation. For example fuel consumption is about 18% and particle mass emissions were around 30-50% higher during cold start.

Most motorcycles on the road still use a carburettor for air/fuel mixture preparation, do not have a catalyst, and have a manual choke for cold-start fuel enrichment. However, increasing numbers of new motorcycles are equipped with fuel injection and electronic mixture control, often in combination with a catalyst. In addition, the share of new mopeds (and some motorcycles) equipped with an automatic choke is increasing. Several studies have dealt with the topic of cold-start emissions from two-wheel vehicles (Czerwinski *et al.*, 2001, 2002a, 2002b; Weilenmann *et al*., 2002). In these studies measurements were conducted using various urban test cycles with cold and hot engines, but only a few vehicles were tested. Cold-start emission factors for two-wheel vehicles have recently been derived in the ARTEMIS project, based upon a larger database (Elst *et al*., 2006).

2.2.3 Cycle load

Weilenmann (2001) investigated the influence of various factors on cold-start emissions using a sample of six Euro 2 petrol cars. The first part of this study investigated the effect of cycle load after a cold start at an ambient temperature of 23°C. Five different driving cycles of gradually increasing average load were used:

(i) A real-world stop-and-go cycle, repeated five times.

(ii) The urban part (ECE cycle) of the New European Driving Cycle (NEDC) describing a smooth and slow urban journey.

(iii) The FTP-75 cycle as a dynamic, fast urban journey.

(iv) A real-world suburban cycle having an average speed of 80 km h^{-1}, repeated three times.

(v) A real-world highway cycle having an average speed of 120 km h^{-1}, repeated three times.

The results showed that cold-start emissions of CO, HC and NO_x generally increased with cycle load, with CO and HC emissions being lowest over the ECE cycle. NO_x emissions were particularly sensitive to the cycle load, with substantially higher emissions over the 120 km h^{-1} highway cycle than over the other cycles (see Figure 7).

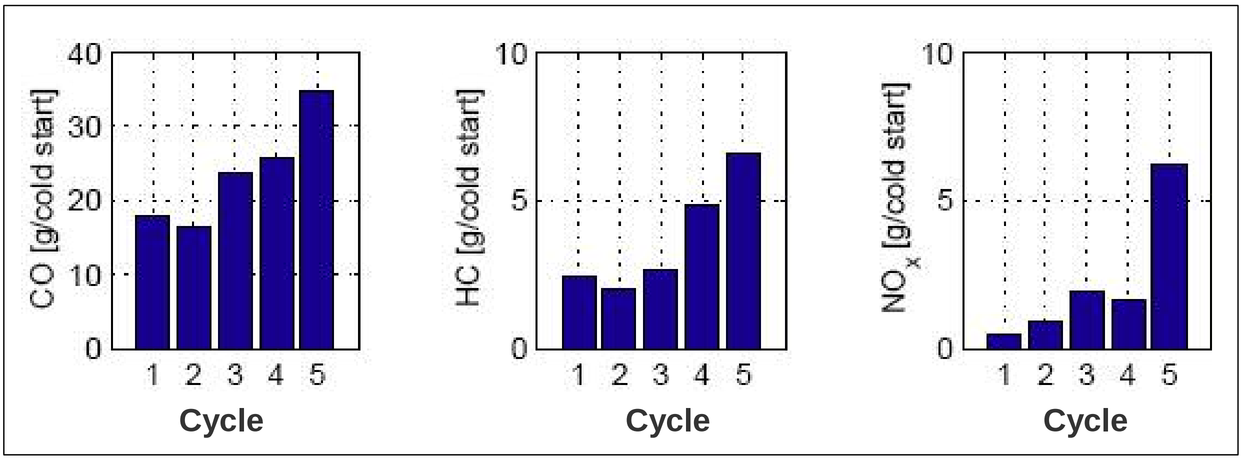

Figure 7: Effect of cycle on average cold-start emissions from Euro 2 petrol cars. Cycle 1 = stop&go, Cycle 2 = ECE, Cycle3 = FTP, Cycle 4 = suburban, Cycle 5 = highway (Weilenmann, 2001).

Although there was a large amount of variation in the cold-start emissions of individual cars, the emission trends over the cycles were similar for all cars. However, over the stop-and-go cycle one small car failed to reach the light-off temperature of the catalyst after 20 minutes at 23°C with speed-dependent cooling, primarily because the engine load was too low.

2.2.4 Ambient temperature

Cold-start emissions and fuel consumption are higher for lower engine and exhaust starting temperatures. As stated earlier, the engine and exhaust temperatures at the start of a trip will depend upon factors such as the length of time the vehicle has been parked, the extent to which the vehicle was fully warmed-up during its previous journey, and the prevailing ambient temperature. The second part of the study by Weilenmann (2001) dealt with the effects of starting temperature on emissions. An urban driving cycle of moderate dynamics and speed was used for cold-start tests at ambient temperatures of 23°C, 10°C and -7°C. This cycle was chosen as the most representative urban cycle from the real-world driving inventory in Switzerland. The 200-second cycle was repeated four times in succession in order to separate the cold-start emissions from the hot emissions. The results are shown in Table 1, and were also compared with earlier studies on Euro 1 cars (Figures 8 to 10).

Table 1: Effect of temperature and cycle on cold-start emissions - average of six Euro 2 petrol cars (Weilenmann, 2001).

Pollutant	Cycle/model and temperature					
	FTP-75 cycle		ECE cycle	Real-world urban cycle		
	Bag 1 - bag 3	Regression model	Regression model	Regression model		
	23°C	23°C	23°C	23°C	10°C	-7°C
CO (g/start)	14.78	17.16	11.51	18.48	46.79	94.84
HC (g/start)	1.41	2.59	1.20	2.38	4.36	11.76
NO_x (g/start)	1.02	1.02	0.519	0.958	1.33	1.31

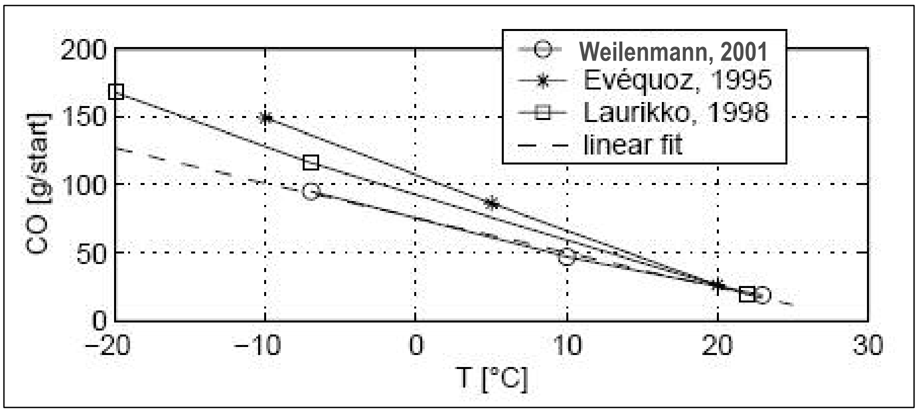

Figure 8: Effect of temperature on CO cold-start emissions (Weilenmann, 2001). The data from Weilenmann relate to Euro 2 cars, whereas the other studies are for Euro 1 cars.

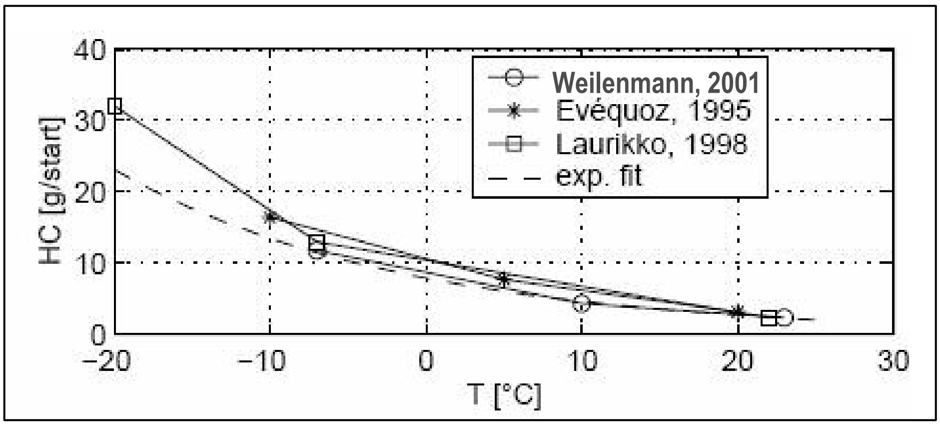

Figure 9: Effect of temperature on HC cold-start emissions (Weilenmann, 2001). The data from Weilenmann relate to Euro 2 cars, whereas the other studies are for Euro 1 cars.

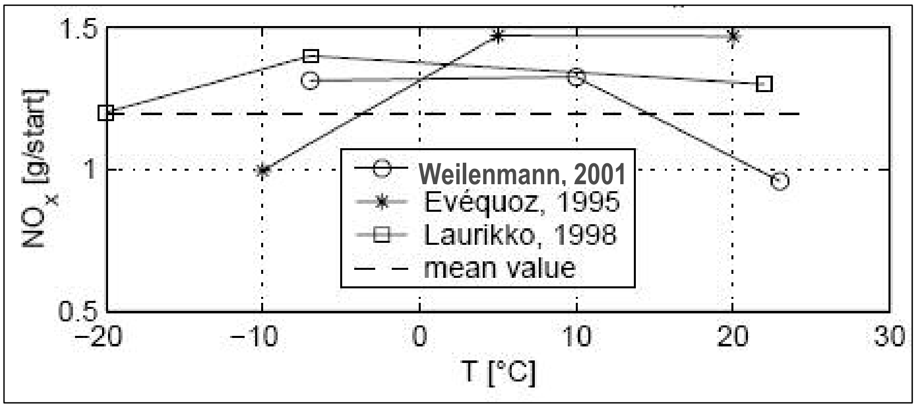

Figure 10: Effect of temperature on NO_x cold-start emissions (Weilenmann, 2001). The data from Weilenmann relate to Euro 2 cars, whereas the other studies are for Euro 1 cars.

CO and HC emissions during these tests were highly sensitive to starting temperature. Lowering the temperature from 23^{o}C (a typical laboratory temperature) to 10^{o}C (a typical UK ambient temperature), increased emissions of CO by a factor of 2.53, HC by a factor of 1.83 and NO_x by a factor of 1.38. The relationship between cold-start CO emissions and temperature range can be assumed to be linear.

Weilenmann *et al.* (2004) performed a further investigation on six Euro 3 petrol cars, six Euro 2 diesel cars and six pre-Euro 1 petrol cars at low ambient temperatures. These measurements were conducted on vehicles belonging to private owners, and were taken straight from the road with no maintenance to obtain real-world emissions. The chassis dynamometer tests were carried out at +23^oC, -7^oC and -20^oC, and using four driving cycles of different average load. In addition to the regulated pollutants, methane, benzene and toluene were measured on-line by chemical ionisation mass spectrometry. Details of the driving cycles used in the study are shown in Table 2.

Table 2: Driving cycles used in the study by Weilenmann *et al.* (2004).

Cycle name	Bag-phase	Average speed (km h^{-1})	Minimum speed (km h^{-1})	Maximum speed (km h^{-1})	Duration (s)	Characteristics
ECE	ECE	18.1	0	50	780	First part of EU legislative cycle, artificial smooth urban driving
FTP-75	FTP-75-I	41.1	0	91.2	505	First part of US legislative cycle - rural driving
	FTP-75-II	25.7	0	55.1	869	Second part of US legislative cycle - urban driving
	FTP-75-III	41.1	0	91.2	505	Identical to part I, but started with a hot engine
IUFC-15	IUFC-15-I	19.0	0	44.0	945	Rural driving (André, 1999)
	IUFC-15-II	19.0	0	44.0	945	Equal to phase I
	IUFC-15-III	19.0	0	44.0	945	Equal to Phase I
IRC-15	IRC-15-I	41.1	0	74.9	630	Rural driving (André, 1999)
	IRC-15-II	41.1	0	74.9	630	Equal to Phase I
	IRC-15-III	41.1	0	74.9	630	Equal to Phase I

Again, cold-start excess emissions were found to be dependent on the driving cycle. With petrol cars, emissions increased at higher loads, such as during suburban or highway driving, but diesel car cold-start emissions decreased at higher loads. Cold-start emissions of CO and HC from Euro 3 petrol cars were significantly lower than those from pre-Euro 1 cars. However, there was no appreciable reduction in the cold-start emissions of benzene from Euro 3 petrol cars compared with pre-Euro 1 petrol cars. The cold-start emissions of Euro 3 petrol cars were 15 times higher at -20^oC than at 23^oC. In addition, the benzene/HC quotient for the Euro 3 petrol cars increased during warm-up phase to about 20%, but was constant at about 3% for pre-Euro-1 petrol cars. Overall cold-start extra emission levels were significantly lower for diesel cars than for petrol cars (Figure 11 and Figure 12). Pre-Euro 1 and Euro 2 diesel cars emitted comparable cold-start CO and NO_x emissions, while HC emissions are somewhat reduced. In contrast to the petrol cars, the diesel cars exhibited a trend in cold-start NO_x emissions for lower temperatures. Diesel and petrol cars exhibited similar HC and CO emission trends with temperature. For diesel cars the benzene/HC and toluene/HC quotients displayed a slightly decreasing trend during engine warm up. Diesel cars emitted significantly more excess CO_2 than petrol cars during the warm-up phase.

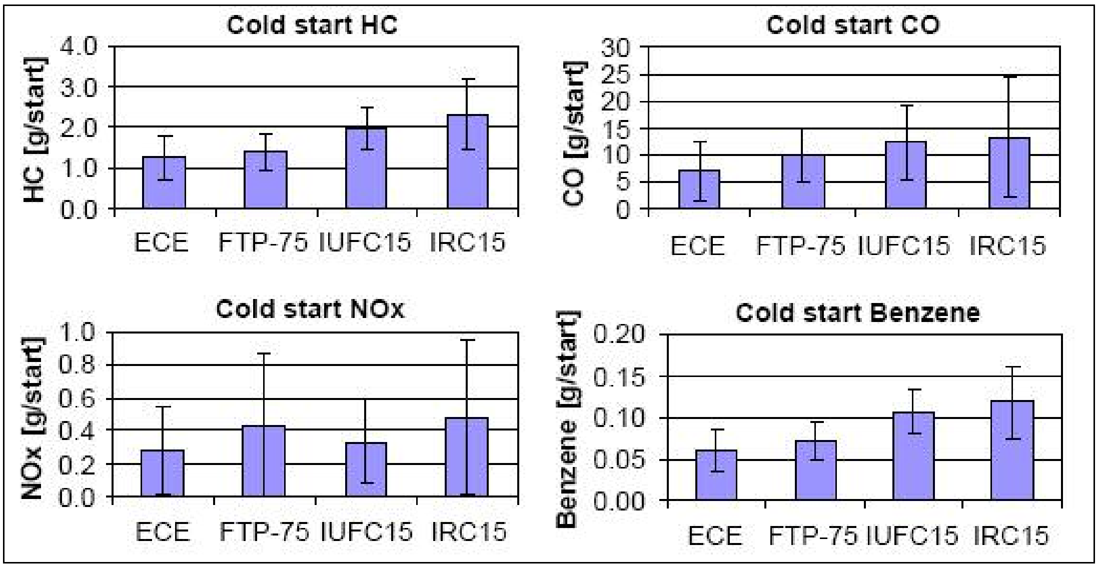

Figure 11: Cold-start emissions petrol cars (Weilenmann *et al.*, 2004).

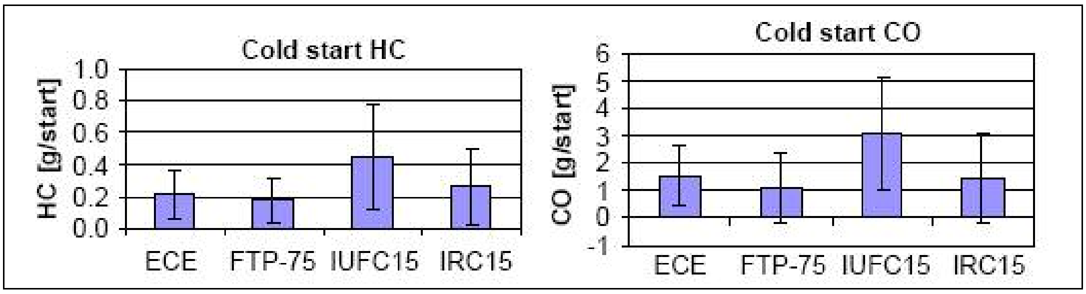

Figure 12: Cold-start emissions diesel cars (Weilenmann *et al.*, 2004).

For the calculation of cold-start emissions in inventories, it is clear that the ambient temperature has to be taken into account. Moreover, the emissions from engines that are started before they have completely cooled down also need to be modelled.

During the development of the EXEMPT model (see Chapter 3), Blaikley *et al.* (2001) generated cold-start emission factors for particulate matter, which are generally lacking in the literature. Only three vehicles were tested (diesel, petrol and petrol direct injection), and the results are shown for two ambient temperatures in Table 3.

Table 3: Excess cold-start PM emissions.

Vehicle	Ambient temperature (°C)	Total hot-start emissions (g/test)	Excess cold-start emissions (g/test)
VW Golf Tdi (diesel)	-7	0.341	0.193
	20	0.298	0.008
Mitsubishi Carisma Gdi (petrol direct-injection)	-7	0.034	0.003
	20	0.037	-
Toyota Avensis (petrol)	-7	0.038	0.051
	20	0.022	0.002

The results suggested that PM emissions from petrol cars were about an order of magnitude lower than those from diesel cars, and that petrol direct-injection vehicles have similar hot-start PM emissions to those of conventional petrol vehicles. Excess cold-start emissions can increase by more than an order of magnitude following a reduction in ambient temperature from 20°C to -7°C. However, these tests were conducted several years ago, and the PM emission characteristics of modern vehicles are rather different.

3 Cold-start emission models

3.1 Overview

In virtually all road transport emission models, total trip-length emissions for a single vehicle of a given type and for a given pollutant are calculated by summing the emissions from three different sources: (i) thermally stabilised engine[7] operation (‘hot’ exhaust emissions), (ii) the warming-up phase (cold-start exhaust emissions) and (iii) fuel evaporation (VOC only):

$$E_{total} = E_{hot} + E_{cold} + E_{evap} \quad \text{(Equation 1)}$$

Where:

E_{total} = Total emissions of the pollutant (g).
E_{hot} = Hot exhaust emissions (g).
E_{cold} = Cold-start exhaust emissions (g).
E_{evap} = Emissions of volatile organic compounds (VOCs) due to evaporation (petrol vehicles only).

In the case of particulate matter, emissions due to tyre wear, brake wear, road surface wear and resuspension also need to be considered.

Different emission factors and different types of activity data are required for each source. The hot emission (E_{hot}) is usually calculated by multiplying an experimentally-derived emission rate for a pollutant and vehicle category ($e_{hot,}$ in g km^{-1}) by the trip length, although approaches vary in complexity. The cold-start emission (E_{cold}) can be calculated using absolute excess emission factors, or by applying a quotient (e_{cold}/e_{hot}) to the hot emission factor (e_{hot}) for each pollutant and vehicle type. An indication of the number of starts in the study area is required, as well as information on vehicle thermal condition and ambient temperature.

Several examples of cold-start emission models are described in outline below. It has not been possible to conduct direct quantitative comparisons between the different models, as the sensitivity of models to certain parameters (such as driving cycle, temperature), combined with differences in modelling approaches input data requirements, means that such comparisons are not meaningful. There is also no independent means of verifying the accuracy of model estimates, and therefore the main criteria for judging the suitability of models are aspects such as how up-to-date and comprehensive models are.

3.2 Model descriptions

3.2.1 COPERT

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

The COPERT methodology, which is described in Appendix B, is one of the most widely used in Europe for estimating emissions at the national level, and it is the preferred method in the European Environment Agency’s Emission Inventory Guidebook (EEA, 2007). For cold-start emissions, COPERT also forms the basis of the NAEI (see Chapter 4).

[7] In this context the word ‘engine’ is used to mean ‘engine and any exhaust aftertreatment devices’.
[8] http://lat.eng.auth.gr/copert/

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

3.2.2 MEET

The European Commission's 4th Framework project MEET (Methodologies for Estimating air pollutant Emissions from Transport) provided a basic Europe-wide procedure for evaluating the impact of transport on air pollutant emissions and energy consumption. It brought together the most comprehensive and up-to-date information on emission rates and activity statistics, which made it possible to estimate the emissions resulting from almost any transport operation. The modes included were road transport, railways, water transport (inland and marine, but excluding leisure activities and fishing), and air traffic. A variety of methods were used to calculate energy consumption and emissions, depending on the pollutant, the transport mode and the vehicle type (European Commission, 1999).

MEET incorporated a slightly different cold-start routine to COPERT II (although COPERT III is a hybrid of COPERT II and MEET), and the approach is described in Appendix C. The method was developed empirically using data assembled from many European test programmes. Sufficient data were only available for cars, for which a distinction could be made between diesel and petrol vehicles with and without a catalyst, but there were too few data from catalyst-equipped diesel vehicles to allow a detailed analysis to be undertaken.

3.2.3 EXEMPT

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

The model is based upon emission measurements on 15 vehicles at various ambient temperatures and vehicle starting temperatures. The measurements included regulated pollutants, benzene, 1,3-butadiene and size-differentiated particulate number. The choice of vehicles reflected the range of vehicle technologies and engine sizes that comprised the anticipated 2005 UK vehicle mix, thus all vehicles were equipped with catalysts and included examples of petrol direct injection, diesel direct injection, diesel engines equipped with an oxidation catalyst, and diesel engines with exhaust gas recirculation. All vehicles were compliant with Euro 2 standards. The emission tests were conducted over the regulatory ECE-15 cycle.

The model is run in three stages:

(i) The initial driving stage. The user defines ambient and engine start temperatures and the distance driven.

(ii) The parking stage. The user defines the ambient temperature and parking time start engine temperature can be specified or calculated from stage (i).

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

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

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

3.2.4 HBEFA

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

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

A revised cold-start model for the Handbook of Emission Factors ought to be available in 2009.

3.2.5 COLDSTART

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

3.2.6 ARTEMIS

The ARTEMIS project commenced in 2000, and had two principal objectives. The first of these was to gain, through a programme of basic research, a better understanding of the causes of the differences in model predictions, and thus to address the uncertainties in emission modelling. The second principal objective was to develop a harmonised methodology for estimating emissions from all transport modes at the national and international levels.

The ARTEMIS project included the development of a new cold-start emission model. André and Joumard (2005) built upon the experience gained during MEET (described above), and collated emissions data from a wide variety of European laboratories (TNO, INRETS, TU-Graz, TÜV, Politecnico di Milano, TRL, EMPA, INTA, VTT, VTI, KTI and LAT). The data included details of the test vehicles (fuel type, model year, engine capacity), driving cycle, ambient temperature, vehicle starting temperature, and the emission measurements under these conditions.

To measure the excess cold-start emissions it was necessary to define when the effect of the warm up phase on emissions has been finished. Since real world driving emissions are constantly variable due to other factors than temperature such as the driving dynamics, the end of the cold-start phase is not easily defined, so a number of approaches were examined in the ARTEMIS programme. The first involved examining the standard deviation of emissions between two consecutive periods and establishing when the emissions have stabilised to a fully warmed up state. The second approach uses a continuous cumulative emission curve. The intercept of the linear regression of this cumulative emission of the hot portion of the curve at zero distance then gives the cold-start emission value. The method chosen for the models developed in this study used both these techniques to determine the cold-start portion.

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

(i) Excess cold-start emission per start.

(ii) Excess cold-start emission from traffic.

(iii) Aggregated cold-start emission factors.

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

In order to illustrate the relative effects of the different parameters, some examples are given for CO in Figure 13 for the influence of average speed and vehicle type, Figure 14 for the influence of ambient temperature and average speed, Figure 15 for the season influence, and Figure 16 for the influence of the hour. The influence of all these parameters depends on the pollutant considered. Nevertheless, the ambient temperature, the average speed and the hour in the day are generally the most important factors. The season, for a given ambient temperature, plays a minor role.

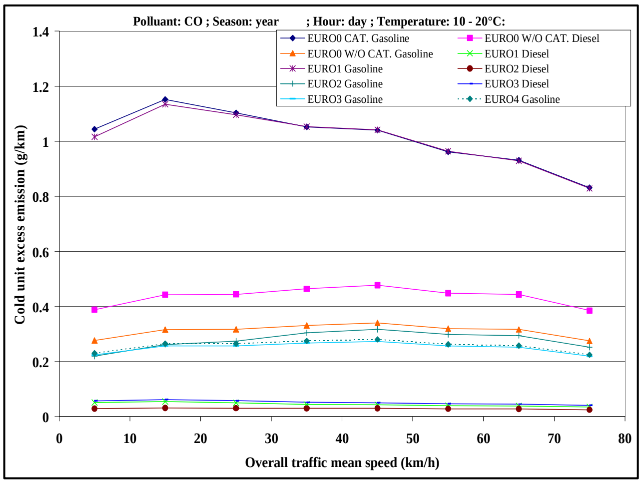

Figure 13: CO cold unit excess emission by average speed and vehicle technology.

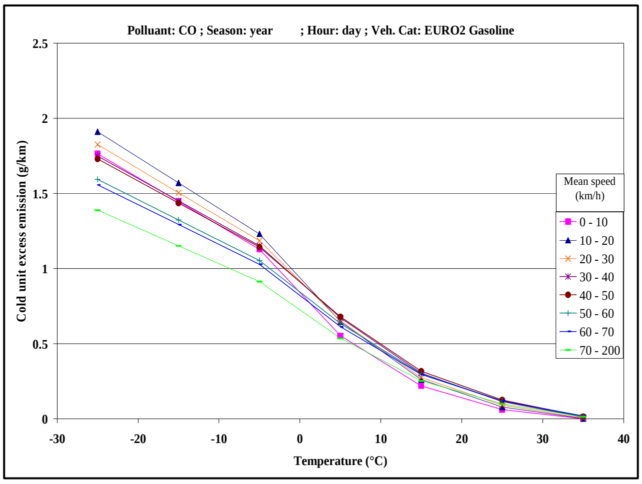

Figure 14: CO cold unit excess emission by ambient temperature and average speed (petrol Euro 2).

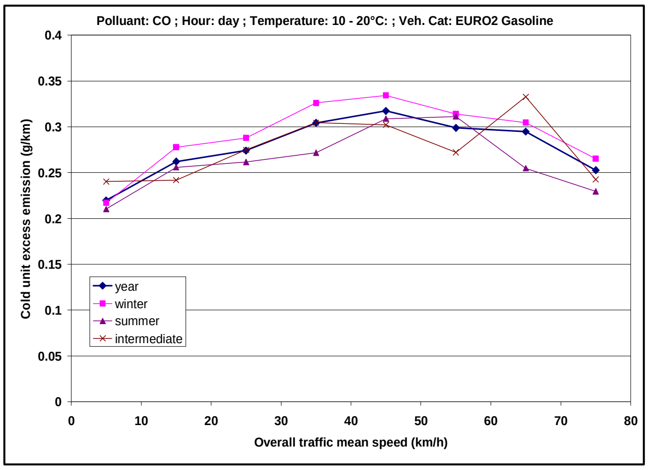

Figure 15: CO cold unit excess emission by season and average speed (petrol Euro 2).

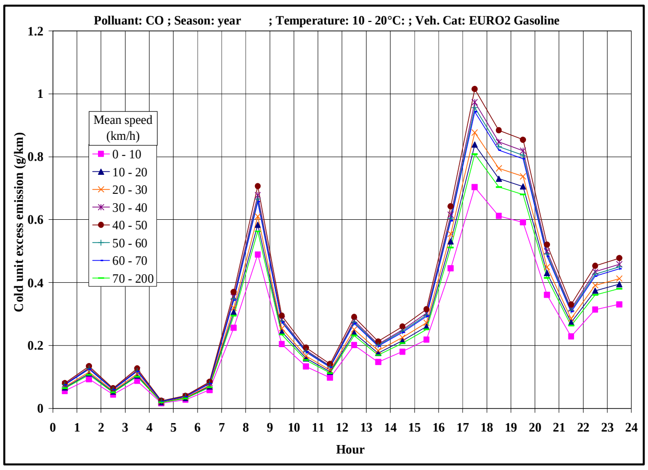

Figure 16: CO cold unit excess emission by hour and average speed (petrol Euro 2).

The three models can be used for numerous vehicle technologies (fuel and emission standard) covering the European situation, and for regulated as well as unregulated pollutants. The models can be applied at different geographic scales: at a macroscopic scale (national inventories) using road traffic indicators and temperature statistics, or at a microscopic scale for a vehicle and a trip.

The complex model is time-consuming to run (several hours on a Unix system), and the input data required are available to few model users. For specific locations INRETS are able to run the complex model for the local condition, assuming the relevant input data are available. Where a model user does not have access to the necessary activity statistics, the use of the third model is recommended. According to André and Joumard (2005), this third model should replace the COPERT III cold-start model for use in Europe.

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

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

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

3.2.7 PHEM

One of the main aims of ARTEMIS and the COST Action was to develop a model capable of accurately simulating emission factors for all types of HDV and passenger car over any driving pattern and - in the case of HDVs - for various vehicle loads and gradients; the latter greatly influence driving behaviour and emission levels from HDVs. The resulting tool - PHEM (Passenger car and Heavy-duty Emission Model) - estimates fuel consumption and emissions based on the instantaneous engine power demand and engine speed during a driving pattern specified by the user (Rexeis *et al*., 2005).

After building and testing the model for warm engine conditions it was decided to expand PHEM for simulating cold-start emissions. The initial effort focussed on modelling cold-start emissions from passenger cars, and particular attention was paid to the designing a method which was valid for simulating cold starts under any driving conditions and ambient temperature - a feature which usually has not been covered by other emission models (Engler *et al.*, 2001). The approach used in PHEM to model cold-start emissions is described in Appendix E.

4 The current NAEI cold-start model

Details of the full NAEI methodology are available from the NETCEN web site[9], and the methodology is also described 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, based on these two sources and further relevant information provided by TRL, was also summarised in the Task 1 Report by Boulter *et al*. (2009). The specific method for estimating cold-start emissions is explained in more detail below.

4.1 Calculation method

The NAEI procedure for estimating cold-start emissions is essentially taken from COPERT II (Ahlvik *et al*., 1997) (see Section 3.2.1), including the equations relating e^{cold}/e^{hot} to ambient temperature for each pollutant and vehicle type, and the equation for the β parameter (the terms are explained in Appendix B):

$$\beta = 0.698 - 0.051 \cdot l_{trip} - (0.01051 - 0.000770 \cdot l_{trip}) \cdot t_a \quad \text{(Equation 2)}$$

The form of the method was not updated for COPERT III (see Appendix B), but some of the coefficients in the equations were modified slightly.

The methodology is used to estimate annual UK cold-start emissions of NO_x, CO and NMVOCs from petrol and diesel cars and LGVs. Emissions are calculated separately for catalyst and non-catalyst petrol vehicles. Fewer cold-start emissions data are available for heavy-duty vehicles, and these are assumed to be negligible. Cold-start emissions of unregulated pollutants are not calculated. NETCEN apply scaling factors for the change in cold and hot emissions due to fuel quality and take account of the uptake rate of the fuel in a given year.

Emissions are calculated for the one-year period covered by the inventory, and shorter time periods are not considered. The equations are used with an annual mean temperature for the UK of 11^{o}C, which is based on historic trends in Meteorological Office data for ambient temperatures over different parts of the UK. An average trip length for the UK of 8.4 km is used, taken from Andre *et al.* (1993). This gives a value for β of 0.23. All cold-start emissions are assumed to apply to urban driving.

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

4.2 Potential weaknesses in the NAEI cold-start model

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

- The approach is based on the equations and coefficients from COPERT II. These are now rather old data, and were updated in 2000 in COPERT III. A draft version of the COPERT 4 methodology (December 2008) is now available.
- The NAEI does not include cold-start emission estimates for heavy-duty vehicles (considered to be negligible) and motorcycles (presumably due to the lack of data).

[9] http://www.aeat.co.uk/netcen/airqual/naei/annreport/annrep99/app1_29.html

- The cold-start emission factors currently in use have been obtained using either the 6 km-long US FTP cycle or the 4 km-long ECE 15 cycle. The emissions calculated using these emission factors will therefore be different to the real-world emissions associated with trips over other distances. For example, most journeys in the UK are of short duration and take place in urban areas. These journeys will start (and many of them will end) with the vehicle significantly below its normal operating temperature.
- The NAEI emission factors relate to starts conducted with the engine and catalyst components at the prevailing ambient temperature. However, the component temperatures will take time to gradually cool down to the ambient level. These will usually be somewhere intermediate between the operating and ambient temperature and dependant on length of time since the vehicle was last used. As a consequence the simple application of the NAEI of the cold-start penalty to two thirds of all trips may not accurately allow for the occurrence of many starts from intermediate temperatures.

5 Summary and recommendations

5.1 Summary

5.1.1 Factors affecting cold-start emissions

Exhaust emissions of regulated pollutants are higher during the cold-start phase than when the engine, catalyst, drive train and tyres are at their design temperatures. This is due to a combination of incomplete fuel combustion in the engine, catalyst inefficiency, and increased friction in the engine and drive train and at the tyre-road interface. These effects have been reasonably well documented, and studies have also dealt with cold-start effects in relation to parameters such as driving cycle characteristics and vehicle technology (or legislation).

The studies which have been reviewed have shown that:

- For the regulated pollutants, excess cold-start emissions of CO and HC are significantly lower for diesel cars than for petrol cars. However, diesel cars emit significantly more additional CO_2 than petrol cars during the cold-start phase. In the case of NO_x, petrol cars from Euro 1 onwards have a small excess emission during cold starting, but for diesel cars there may be a slightly positive or slightly negative excess emission.
- For diesel cars, excess cold-start CO, CO_2 and HC emissions are not strongly dependent upon emission legislation.
- Cold-start emissions HC and NO_x from petrol vehicles have decreased substantially between Euro 1 and Euro 4.
- There has been no appreciable reduction in the cold-start emissions of benzene from Euro 3 petrol cars compared with pre-Euro 1 petrol cars.
- Cold-start emissions of CO, HC and NO_x generally increase with the cycle load during the cold-start phase, NO_x particularly so. Motorway-type driving results in higher loads than urban driving.
- Cold-start emissions from all cars increase substantially at lower ambient temperatures.
- Even after the catalyst has warmed up, prolonged low speed or low load operations (such as idling) may cause the catalyst temperature to drop below the optimum operating level, although this is not normally considered to constitute cold-start operation. In some experiments over stop-and-go driving cycles, some small cars have failed to reach the light-off temperature of the catalyst after 20 minutes, primarily because the engine load was too low. In some modern vehicles the catalyst is placed nearer to the engine exhaust manifold ('close coupling') in order to minimise the possibility of this happening and to reduce the overall cold start effects.

5.1.2 Cold-start emission models

This Report has highlighted a number of potential sources of data which might be used to update and refine the modelling approach for cold-start emissions which is currently used in the NAEI. Several cold-start models were reviewed:

- COPERT
- MEET
- EXEMPT
- HBEFA
- COLDSTART
- ARTEMIS
- PHEM

The calculation method used in the NAEI was also described, and some potential weaknesses were identified. Models which use more sophisticated approaches and incorporate more recent data are now available. The data used to generate the cold-start emission factors are now rather old, and may no longer be representative of modern vehicles.

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

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

5.2 Recommendations

The main issues relating to the use of the ARTEMIS models in the NAEI are their complexity and the availability of relevant input data. The full ARTEMIS model currently takes several hours to process the required input data. The third - and simplest - ARTEMIS model would be the easiest to implement, but it is not clear why emissions are presented in terms of grammes per vehicle-kilometre rather than grammes per start.

A more detailed examination of the ARTEMIS models would be required before one of them could be incorporated into the NAEI. For example, a survey of parking duration may be necessary to make full use of the ARTEMIS models capabilities. Alternatively, it may be possible to simplify the models so that most of the important variables are included. If a single cold-start factor was required for each vehicle class (independent of vehicle speed), this could also be calculated using an average trip distance and speed, but it would mean that much of the data generated in the ARTEMIS programme would be ignored.

On balance, the main conclusion is that - before any more detailed modelling of cold-start emissions is attempted - the current NAEI model (which is based upon COPERT II) ought to be updated to reflect COPERT 4. COPERT 4 does not contain any new emission factors.

In fact, at the time of writing the compilers of COPERT were improving the methodology for cold-start emissions. In addition, a revised cold-start model for the Handbook of Emission Factors ought to be available in 2009. When these are published they should also be considered for inclusion in the NAEI.

Consequently, it is not possible to give new emission factors for the most recent car and LGV categories at this stage. Cold-start emission factors for heavy goods vehicles were presented in MEET, and PHEM contains a cold-start modelling routine. However, the MEET data are now rather old and PHEM is not freely available at present.

For motorcycles, on the other hand, cold-start emission factors have been determined in the ARTEMIS project, and these are available for use in the NAEI. These have not been included in COPERT, and it is not clear whether this is the intention. Cold-start emission factors were determined by using all available data for the relevant vehicle categories defined in ARTEMIS (Elst *et al.*, 2006). Although the most relevant categories were included in the sample, for some categories there was still a lack of data. For these categories cold-start emissions were estimated based on observed trends and expert judgement. The additional emissions for cold start are given in Table 4 and Table 5.

Table 4: Excess cold-start emissions for 2-stroke motorcycles (per start).

Engine capacity (cm^3)	Legislative category	CO (g)	HC (g)	NO_x (g)	FC [10] (cm^3)	Ultimate CO_2 [11] (g)
<50	Pre-Euro 1	4	6	0	9	20
	Euro 1	4	6	0	9	20
	Euro 2	4	6	0	9	20
	Euro 3	4	6	0	9	20
50-150	Pre-Euro 1	4	6	0	9	20
	Euro 1	4	6	0	9	20
	Euro 2	4	6	0	9	20
	Euro 3	4	6	0	9	20
151-250	Pre-Euro 1	4	6	0	9	20
	Euro 1	4	6	0	9	20
	Euro 2	4	6	0	9	20
	Euro 3	4	6	0	9	20
251-750	Pre-Euro 1	4	6	0	9	20
	Euro 1	4	6	0	9	20
	Euro 2	4	6	0	9	20
	Euro 3	4	6	0	9	20

Table 5: Excess cold-start emissions for 4-stroke motorcycles (per start).

Engine capacity (cm^3)	Legislative category	CO (g)	HC (g)	NO_x (g)	FC [10] (cm^3)	Ultimate CO_2 [11] (g)
<50	Pre-Euro 1	5.0	1.3	0.10	17	40
	Euro 1	4.5	1.2	0.15	17	40
	Euro 2	4.0	1.1	0.20	17	40
	Euro 3	3.5	1.0	0.25	17	40
50-150	Pre-Euro 1	5.0	1.3	0.10	17	40
	Euro 1	4.5	1.2	0.15	17	40
	Euro 2	4.0	1.1	0.20	17	40
	Euro 3	3.5	1.0	0.25	17	40
151-250	Pre-Euro 1	5.0	1.3	0.10	17	40
	Euro 1	4.5	1.2	0.15	17	40
	Euro 2	4.0	1.1	0.20	17	40
	Euro 3	3.5	1.0	0.25	17	40
251-750	Pre-Euro 1	22	3.5	0.06	17	40
	Euro 1	20	3.0	0.09	17	40
	Euro 2	18	2.5	0.12	17	40
	Euro 3	16	2.0	0.15	17	40
>750	Pre-Euro 1	22	3.5	0.06	17	40
	Euro 1	20	3.0	0.09	17	40
	Euro 2	18	2.5	0.12	17	40
	Euro 3	16	2.0	0.15	17	40

[10] Fuel consumption is calculated applying the carbon balance method (using *measured* CO_2, CO and HC emissions)
[11] CO_2 emissions based on fuel consumption - not exhaust CO_2 - assuming that all molecules containing carbon are oxidised to CO_2**.**

6 References

Ahlvik P, Eggleston S, Gorißen N, Hassel D, Hickman A J, Joumard R, Ntziachristos L, Rijkeboer R, Samaras Z and Zierock K-H (1997). COPERT II: Computer Programme to Calculate Emissions from Road Transport - Methodology and Emission Factors. European Topic Centre on Air Emissions, European Environment Agency, April 1997.

André J-M and Joumard R (2005). Modelling of cold start excess emissions for passenger cars. INRETS Report LTE0509. Laboratoire Transports et Environnement, INRETS, case 24, 69675 Bron cedex, France.

Andre M, D Hassel, A J Hickman and R Joumard (1993). Cycles de conduite realistes pour la mesure des emissions de polluants et consommation des vehicules legers sur banc B rouleaux. *Science of the Total Environment, Vol.* 134, pp. 171-187.

André M, Hammarström U and Reynaud I (1999). Driving statistics for the assessment of air pollutant emissions from road transport, INRETS report, LTE9906, Bron, France.

Barlow T J and Boulter P G (2009). Emission factors 2009: Report 2 - A review of the average-speed approach for estimating hot exhaust emissions from road vehicles. TRL Report 355. TRL limited, Wokingham.

Barlow T J, Hickman A J and Boulter P (2001). Exhaust emission factors 2000 database and emission factors. TRL Unpublished Report PR/SE/230/00. Transport Research Laboratory, Crowthorne.

Barlow T J, Latham S, McCrae I S and P G Boulter (2009). A Reference Book of Driving Cycles for Use in the Measurement of Road Vehicle Emissions. TRL Report PPR354. TRL limited, Wokingham.

Blaikley D C W, Smith A P, Feest E A and Reading A H (2001). UG219 TRAMAQ - cold-start emissions. Summary report, AEAT/ENV/R/0638 Issue 1, May 2001.

Boulter P G (1997). Environmental traffic management: A review of factors affecting cold-start emissions. TRL Report 270. Transport Research Laboratory, Crowthorne.

Boulter P G (2009). Emission factors 2009: Report 6 - deterioration factors and other modelling assumptions for road vehicles in the NAEI. TRL Report PPR359. TRL limited, Wokingham.

Boulter P G and Latham S (2009). Emission factors 2009: Report 5 - a review of the effects of fuel properties on road vehicle emissions. TRL Report PPR358. TRL limited, Wokingham.

Boulter P G, Barlow T J, Latham S and McCrae I S (2009a). Emission factors 2009: Report 1 - a review of methods for determining hot exhaust emission factors for road vehicles. TRL Report PPR353. Transport Research Laboratory, Wokingham.

Boulter P G, Barlow T J and McCrae I S (2009b). Emission factors 2009: Report 3 - exhaust emission factors for road vehicles in the United Kingdom (2009). TRL Report PPR356. TRL Limited, Wokingham.

Boulter P G, Barlow T J, McCrae I S and Latham S (2009c). Emission factors 2009: Final summary report. TRL Report PPR361. TRL Limited, Wokingham.

Choudrie S L, Brown L, Milne R, Murrells T P, Passant N, Thistlethwaite G, Watterson J D and Jackson J (2008). UK Greenhouse Gas Inventory, 1990 to 2006. AEA Technology, Harwell, Oxfordshire. ISBN 0-9554823-4-2.

Czerwinski J, Comte P and Wili P (2001). Summer cold start, limited emissions and nanoparticulates of 4-stroke-motorcycles. Final report of the contract BUWAL / VLR.01.23.

Czerwinski J, Comte P, Wili P, Matter U and Mosimann T (2002a). Summer cold start and emissions of different two-wheel vehicles. Final report of the contract BUWAL/ VLR.02.05.

Czerwinski J, Comte P, Napoli S and Wili P (2002b). Summer Cold Start and Nanoparticulates of Small Scooters. SAE-Paper 2002-01-1096, AFHB, Detroit, March 4-7, 2002.

Duboudin C and Crozat C (2002). Analyse de la méthodologie COPERT III (Analysis of the COPERT III methodology). SCM report, Paris, 152 p.

EEA (2007). EMEP/CORINAIR Emission Inventory Guidebook – 2007. Technical report No 16/2007 3rd edition. European Environment Agency, Copenhagen.

Eggleston S, Gorißen N, Joumard R, Rijkeboer R C, Samaras A and Zierock K-H (1989). CORINAIR Working Group on Emissions Factors for Calculating 1985 Emissions from Road Traffic. Volume 1: Methodology and Emission Factors. Final Report Contract No. 88/6611/0067, EUR 12260 EN.

Eggleston S, Gaudioso D, Gorißen N, Joumard R, Rijkeboer R C, Samaras Z and Zierock K-H (1993). CORINAIR Working Group on Emissions Factors for Calculating 1990 Emissions from Road Traffic. Volume 1: Methodology and Emission Factors. Final Report, Document of the European Commission ISBN 92-826-5571-X.

Elst D A M M, Gense N L J, Vermeulen R J and Steven H (2006). ARTEMIS Workpackage 500 Final Report (Deliverable 5). TNO-Automotive, Delft.

Engler D, Hausberger S and Blassnegger J (2001). Cold start emissions of heavy-duty vehicles. SAE Technical Paper Series 2001-01-077. 5th International Conference on Internal Combustion Engines. Capri, 23-27 September2001. Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology, Graz, Austria

European Commission (1999). MEET - Methodology for calculating transport emissions and energy consumption. Office for Official Publications of the European Communities, L-2985 Luxembourg.

Evéquoz R, Keller M, Heldstab J and Kessler H (1995). Luftschadstoff- Emissionen des Strassenverkehrs 1950 – 2010, Swiss Agency for the Environment, Forest and Landscape (BUWAL). Schriftenreihe Umwelt Nr. 255.

Gkatzoflias D, Kouridis, Ntziachristos L and Samaras Z (2007). COPERT 4. Computer program to calculate emissions from road transport. User Manual (version 5.0). Published by ETC-ACC (European Topic Centre on Air and Climate Change).

Hammarström U (2002). Betydelsen av korta motoravstängningar och körtid för avgasemissioner fran bensindrivna bilar med och utan katalysator. VTI meddelande, 931, Sweden.

Hammarström U and H Edwards (1997). COLDSTART (Draft). Swedish National Road and Research Institute (VTT), Linköping, Sweden.

Hausberger S (1997). Globale Modellbildung für Emissions- und Verbrauchsszenarien im Verkehrssektor (Global Modelling of Scenarios Concerning Emission and Fuel Consumption in the Transport Sector); *Dissertation am Institut für Verbrennungskraftmaschinen und Thermodynamik der TU-Graz*. Technical University of Graz, Austria.

Heeb N, Forss A-M and Wilhelm P (2001). Comparison of methane, benzene and alkyl benzenes cold start emission data of Euro 1 and Euro 2 three-way catalyst passenger cars and light duty vehicles from time resolved exhaust gas analysis. Proceedings of 10th Transport and Air Pollution Symposium, Boulder Colorado USA, 17 – 19 September 2001.

INFRAS (2004). Handbook of Emission Factors for Road Transport, Version 2.1. INFRAS, Berne, Switzerland, February 2004.

Joumard R (2005). Personal communication to Paul Boulter at TRL Ltd.

King K, Sturman J and Passant N (2006). NAEI: UK emission mapping methodology 2003. NETCEN Report AEAT/ENV/R/2259.

Latham S and Boulter P G (2009). Emission factors 2009 – Report 7 - a review of the NAEI methodology for modelling evaporative emissions. TRL Report PPR360. Transport Research Laboratory, Wokingham.

Latham S, Petley L J, Hickman A J and Cloke J (2000). A review of available road traffic emission models. TRL Project Report PR/SE/561/99. Transport Research Laboratory, Crowthorne.

Laurikko, J (1998). On exhaust emissions from petrol-fuelled passenger cars at low ambient temperatures, dissertation, VTT publication 348. VTI, Espoo, Finland.

Ntziachristos L and Samaras Z (2000). COPERT III. Computer program to calculate emissions from road transport. Methodology and emission factors (version 2.1). Technical Report No. 49. European Environment Agency, Copenhagen.

Rexeis M, Hausberger S, Riemersma I, Tartakovsky L, Zvirin Y and Erwin C (2005). Heavy-duty vehicle emissions. Final Report of WP 400 in ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems); DGTREN Contract 1999-RD.10429; University of Technology, Graz; report no: I 02/2005/Hb 20/2000 I680.

Schweizer T, Rytz C, Heeb N and Mattrel P (1997). Nachführung der Emissionsgrundlagen Strassenverkehr - Teilprojekt Emissionsfaktoren - Arbeiten 1996. EMPA Bericht, Nr. 161’150. EMPA, Switzerland.

Weilenmann M (2001). Cold start and cold ambient emissions of Euro 2 cars. Proceedings of 10th International Symposium on Transport and Air Pollution, September 17 – 19 2001 – Boulder, Colorado USA EMPA, Überlandstrasse 129, 8600 Dübendorf, Switzerland.

Weilenmann M, Forss A M and Heeb N (2002). Winter Cold start of Two-Wheelers. EMPA Untersuchung-sbericht Nr. 202 114a, ISSN 1424-253. Swiss Federal Laboratories for Materials Testing and Research.

Weilenmann M, Soltic P, Saxer C, Forss A and Heeb N (2004). Regulated and nonregulated diesel and petrol cold-start emissions at different temperature, EMPA Swiss Federal Laboratories for Materials Testing & Research, Section I.C. Engines/Furnaces, Ueberlandstrasse 129, 8600 Dübendorf, Switzerland.

Weilenmann M, Soltic P, Saxer C, Forss A-M and Heeb N (2005). Regulated and nonregulated diesel and gasoline cold start emissions at different temperatures. *Atmospheric Environment*, Vol. 39, pp. 2433–2441.

Zallinger M, Anh T and Hausberger S (2005). Improving an instantaneous emission model for passenger cars. Proceedings of the 14th International Conference on Transport and Air Pollution, Graz, Austria, 1-3 June 2005. Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology, Austria.

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: COPERT methodology

B1 COPERT III

In COPERT III, excess cold-start emissions of regulated pollutants are estimated per kilometre driven using the following equation:

$$E_{cold,i,j} = \beta_{i,j} \times N_j \times M_j \times e_{hot,i,j} \times [(\frac{e_{cold}}{e_{hot}})_{i,j} - 1] \quad \text{Equation B1}$$

where:

E_{cold}	=	Cold-start emission of the pollutant *i* (for the reference year) and vehicle category *j*.
$ß_{i,j}$	=	Fraction of mileage driven with cold engines or catalyst operated below the light-off temperature for pollutant *i* and vehicle category *j* (g).
N_j	=	Number of vehicles in class *j* in circulation in vehicle category *j*.
M_j	=	Annual mileage per vehicle (km veh^{-1}) in category *j*.
$e_{hot,i,j}$	=	The hot emission factor for pollutant *i* and vehicle category *j* (g km^{-1}).
$(e_{cold}/e_{hot})_{i,j}$	=	Cold/hot emission quotient for pollutant *i* and vehicles class *j*.

The quotient of cold and hot emissions (e_{cold}/e_{hot}) is therefore applied to the regional or national fraction of kilometres driven with a cold engine (*ß*), and is multiplied by the aggregate hot emission estimate for the area. Values of e_{hot} are given in the COPERT III documentation (Ntziachristos and Samaras, 2000), and are not repeated here. For unregulated pollutants, including nitrous oxide, ammonia and PAHs, there is no separate methodology for estimating cold-start emissions, and only bulk (hot + cold) emission factors are provided. The *ß* parameter depends upon ambient temperature (t_a) and pattern of vehicle use, and the trip length (l_{trip}), and is given by:

$$\beta = 0.6474 - 0.02545 \times l_{trip} - (0.00974 - 0.000385 \times l_{trip}) \times t_a \quad \text{Equation B2}$$

Average national values are usually used for the input variables t_a[12] and l_{trip}. These factors may vary from country to country. Different driving behaviour (varying trip lengths), as well as climate with varying time (and hence distance) required to warm up the engine and/or the catalyst affect the fraction of distance driven with cold engines. However, since information on l_{trip} is not available in many countries for all vehicle classes, simplifications have been introduced for some vehicle categories. For the UK, an average value of l_{trip} of 10 km is given. The value of the e_{cold}/e_{hot} quotient also depends on vehicle speed, ambient temperature, and the pollutant considered. These dependencies are partially accounted for in COPERT.

Although the model from COPERT 90 is still used in COPERT III for the calculation of emissions during the cold-start phase, new emission quotients were introduced for catalyst-equipped petrol vehicles. These were based on information from the MEET project (see Section 3.2). However, according to Ntziachristos and Samaras, (2000), the application of the full MEET approach needed to be further refined and tested. Therefore, an intermediate step was adopted for COPERT III.

Cold-start emissions are mainly attributable to urban driving, as the majority of trip start to urban areas. However, a portion of cold-start emissions may also be attributable to rural conditions where the mileage fraction driven with non-thermally stabilised engine conditions (β parameter) exceeds the mileage share attributed to urban conditions (S_{urban}). This case requires a transformation of Equation B1:

If $\beta > S_{urban}$,

$$E_{cold\,(urban)i,j} = S_{urban,i,j} \times N_j \times M_j \times e_{hot\,(urban)\,i,j} \times (e_{cold}/e_{hot})_{i,j} - 1) \quad \text{Equation B3}$$

$$E_{cold\,(rural)i,j} = (\beta_{i,j} - S_{urban,i,j}) \times N_j \times M_j \times e_{hot\,(urban)\,i,j} \times (e_{cold}/e_{hot})_{i,j} - 1) \quad \text{Equation B4}$$

[12] The average monthly temperature can be used. The maximum temporal resolution for cold start emissions is one month.

In this case, it is considered that the total mileage driven under urban conditions corresponds to warming-up conditions, while the remaining over-emissions are attributed to urban conditions. The case demonstrated by Equations B4 and B5 is rather extreme for a national inventory, and can only happen in cases where a very small value has been provided for l_{trip}.

Petrol cars

Pre-Euro 1 vehicles

Table B1 gives the e_{cold}/e_{hot} quotients for pre-Euro 1 vehicles. The β parameter is calculated using Equation B2.

Table B1: Values of the e_{cold}/e_{hot} quotient for pre-Euro 1 petrol cars and light goods vehicles (Ntziachristos and Samaras, 2000).

Pollutant	Temperature range (°C)	e_{cold}/e_{hot}
CO	-10 to 30	3.7 - 0.09 x t_a
NO_x	-10 to 30	1.14 - 0.006 x t_a
VOC	-10 to 30	2.8 - 0.06 x t_a
FC	-10 to 30	1.47 - 0.009 x t_a

Euro 1 vehicles

Emissions of catalyst-equipped (Euro 1) vehicles during the warm-up phase are significantly higher than during stabilised thermal condition due to the negligible efficiency of the catalytic converter at temperatures below the light-off. Therefore, the effect of cold start has to be modelled in detail in the case of Euro 1 vehicles. Table B2 provides e_{hot}/e_{hot} quotients for three main pollutants and fuel consumption.

Table B2: Values of the e_{cold}/e_{hot} quotient for Euro 1 and later petrol cars and light goods vehicles (Ntziachristos and Samaras, 2000) ($e_{cold}/e_{hot} = a\text{x}v + b\text{x}t_a + c$).

Pollutant	Engine size range (l)	Speed range (km h^{-1})	Temperature range (°C)	*a*	*b*	*c*
CO	<1.4 l	5-25	-20 to 15	0.156	-0.155	3.519
		26-45	-20 to 15	0.538	-0.373	-6.24
		5-45	>15	8.032E-02	-0.444	9.826
	1.4-2.0	5-25	-20 to 15	0.121	-0.146	3.766
		26-45	-20 to 15	0.299	-0.286	-0.58
		5-45	>15	5.03E-02	-0.363	8.604
	>2.0	5-25	-20 to 15	7.82E-02	-0.105	3.116
		26-45	-20 to 15	0.193	-0.194	0.305
		5-45	>15	3.21E-02	-0.252	6.332
NO_x	<1.4	5-25	> -20	4.61E-02	7.38E-03	0.755
		26-45	> -20	5.13E-02	2.34E-02	0.616
	1.4-2.0	5-25	> -20	4.58E-02	7.47E-03	0.764
		26-45	> -20	4.84E-02	2.28E-02	0.685
	>2.0	5-25	> -20	3.43E-02	5.66E-03	0.827
		26-45	> -20	3.75E-02	1.72E-02	0.728
VOC	<1.4	5-25	-20 to 15	0.154	-0.134	4.937
		26-45	-20 to 15	0.323	-0.240	0.301
		5-45	>15	9.92E-02	-0.355	8.967
	1.4-2.0	5-25	-20 to 15	0.157	-0.207	7.009
		26-45	-20 to 15	0.282	-0.338	4.098
		5-45	>15	4.76E-02	-0.477	13.44
	>2.0	5-25	-20 to 15	8.14E-02	-0.165	6.464
		26-45	-20 to 15	0.116	-0.229	5.739
		5-45	>15	1.75E-02	-0.346	10.462
FC	All classes		-10 to 30	0	-0.009	1.47

The values proposed are a result of fitting the existing COPERT methodology to the results from MEET (European Commission, 1999), and are a function of ambient temperature and average trip speed. Two speed regions have been introduced (5-25 km h^{-1} and 25-45 km h^{-1}). As in the case of hot emission factors, the value introduced for speed should correspond to the mean trip speed and not to the instantaneous speed. The speed range proposed is sufficient to cover most applications because cold-start over-emissions are, in principle, allocated to urban driving only.

At relatively high temperatures the proposed functions have values less than one. In such cases a value of one should be used. Generally, cold-start effects become negligible above 25°C for CO, and above 30°C for VOCs.

The mileage fraction driven during the warming up phase is calculated by means of Equation B2. After calculating the β-parameter and the e_{cold}/e_{hot} quotients, the application of Equations B1, B3 and B4 is straightforward.

<u>Post-Euro 1 vehicles</u>

For post-Euro 1 vehicles the emission reduction compared with Euro 1 during the warm-up phase mainly arises from the reduced time which is required from new catalytic systems to reach the light-off temperature. This time reduction also reflected in a decrease in the distance travelled with a partially warmed engine and/or exhaust aftertreatment device. Therefore, reduced cold-start emissions are simulated via a reduction in the β parameter. Table B3 provides the reduction factors ($bc_{i,j}$) to be applied to the β parameter.

Table B3: *ß* parameter reduction factors (*bc*) for post-Euro 1 petrol vehicles compared with Euro I (Ntziachristos and Samaras, 2000).

Emission legislation	CO	NO_x	VOC
Euro 2	0.72	0.72	0.56
Euro 3	0.62	0.32	0.32
Euro 4	0.18	0.18	0.18

It is assumed that the e_{cold}/e_{hot} values for Euro 1 vehicles can also be applied to more recent vehicle classes without further reductions. Therefore, for post-Euro 1 vehicles Equation B1 becomes:

$$E_{cold,i,j} = \quad bc_{i,j} \times \beta_{i,Euro\ I} \times N_j \times M_j \times e_{hot,i,Euro\ I} \times [(\frac{e_{cold}}{e_{hot}})_{i,Euro\ I} - 1] \qquad \text{Equation B6}$$

Petrol light goods vehicles

For petrol light goods vehicles the e_{cold}/e_{hot} quotients for petrol passenger cars (>2.0 l) are used in the absence of more detailed data. In addition, Equations B1, B3 and B4 is applied to pre-Euro 1 vehicles, and Equation B6 to Euro 1 and later vehicles. The β parameter reduction factors from Table B3 are also used.

Diesel cars and light goods vehicles

Cold-start emissions from diesel vehicles are not very significant compared with those from petrol vehicles. No distinction is therefore made between pre-Euro 1 and Euro 1 vehicles The e_{cold}/e_{hot} quotients are provided in Table B4. The reduction factors ($Rf_{i,j}$) proposed for hot emissions are also applicable to cold-start emissions from diesel passenger cars (Table B5). The application of Equation B1 in this case yields:

$$E_{cold,i,j} = \quad \beta_{i,j} \times N_j \times M_j \times (\frac{100 - RF_{i,j}}{100}) \times e_{hot,i,Euro\ I} \times [(\frac{e_{cold}}{e_{hot}})_{i,Euro\ I} - 1] \qquad \text{Equation B7}$$

The β parameter is again calculated using Equation B2 for all classes.

Table B4: Values of the e_{cold}/e_{hot} quotient for diesel cars and light goods vehicles (Ntziachristos and Samaras, 2000).

Pollutant	Temperature range (^oC)	e_{cold}/e_{hot}
CO	-10 to 30	1.9 - 0.03 x t_a
NO_x	-10 to 30	1.3 - 0.013 x t_a
VOC	-10 to 30	3.1 - 0.09 x t_a
PM	-10 to 30	3.1 - 0.1 x t_a
FC	-10 to 30	1.34 - 0.008 x t_a

Table B5: Emission reduction percentages ($RF_{i,j}$) for post-Euro 1 diesel vehicles compared with Euro 1 (Ntziachristos and Samaras, 2000).

Emission legislation	CO (%)	NO_x (%)	VOC (%)	PM %)
Euro 2	0	0	0	0
Euro 3	0	23	15	28
Euro 4	0	47	31	55

Diesel light goods vehicles are treated as passenger cars.

LPG cars

The methodology for petrol cars is also applied to LPG vehicles. However, very few data on cold-start emissions from LPG vehicles were available. Equations B1, B3 and B4 are applied up to Euro 1 vehicles, whilst Equation B6 is applied to post-Euro 1 vehicles. Reduction factors for the β parameter equal those for petrol vehicles.

Table B6: Values of the e_{cold}/e_{hot} quotient for Euro 1 LPG cars (Ntziachristos and Samaras, 2000).

Pollutant	Temperature range (^oC)	e_{cold}/e_{hot}
CO	-10 to 30	3.66 - 0.09 x t_a
NO_x	-10 to 30	0.98 - 0.006 x t_a
VOC	-10 to 30	2.24 - 0.06 x t_a
FC	-10 to 30	1.47 - 0.009 x t_a

Heavy-duty vehicles and motorcycles

Only bulk emission factors are given for heavy-duty vehicles and motorcycles.

B2 COPERT 4

At the time of writing, the compilers of COPERT were working on a new cold-start calculation methodology for inclusion in the COPERT 4 software, which includes more detailed calculations for late-technology vehicles and the improvements brought about by the new emission test at -7 ^{o}C.

Appendix C: MEET methodology

In the MEET model, a reference value for each pollutant and vehicle type (passenger cars only) is defined for the excess emission as the value corresponding to a start temperature of 20°C and an average trip speed of 20 km h^{-1}. The reference value can then be corrected for the actual start temperature and average speed, and also for the distance travelled (as some trips are shorter than the distance needed to fully warm up the engine, and on those trips the total excess emission is not produced). The excess cold-start emission is expressed as follows:

$$E_{cold}(g) = \omega \times [f(V) + g(T) - 1] \times h(d)$$ Equation C1

where:

V = Mean speed in km h^{-1} during the cold period.

T = Temperature in °C (ambient temperature for cold start, engine start temperature for starts at an intermediate temperature).

d = Distance travelled.

ω = Reference excess emission at 20°C and 20 km h^{-1}.

Reference excess emission

The reference value for the excess emission was defined to be the amount produced at an average speed of 20 km h^{-1} with a start temperature of 20°C, and over a trip long enough for the engine to reach its fully warmed-up condition. Because the available data covered a variety of different test conditions, the reference values were derived using an iterative process in which the functional dependencies on speed, temperature and trip length were first determined, and subsequently used to quantify the excess emissions that would be produced under the reference conditions. The values derived in this way are given in Table C1, classified by vehicle type and pollutant.

Table C1: Reference excess cold-start emission (ω) at 20°C and 20 km h^{-1}.

Vehicle category	Pollutant				
	CO_2	CO	HC	NO_x	FC
Petrol non-catalyst cars	144.16	63.51	8.23	-0.30	83.71
Diesel non-catalyst cars	182.57	2.18	0.82	0.06	62.95
Petrol catalyst cars	132.46	28.71	4.62	1.77	59.79
Diesel catalyst cars	153.36	0.74	0.65	0.03	55.4

Effect of average speed

Data from INRETS were used to derive functions to express the excess emissions in terms of the average vehicle speed. These data were chosen because they were measured using a single sample of cars and the tests used realistic driving cycles (many of the other data were derived from tests using legislative driving cycles). Although the data were considered most appropriate to define the basic relationship between excess emissions and average speed, they would not necessarily give the most accurate values for the absolute excess emissions, since they involved only a small number of vehicles. Therefore, a correction was made to bring the data into agreement with the far greater number of results obtained elsewhere. This was done on the basis of measurements over the FTP cycle. Because these functions are used to correct the reference excess emissions, they were finally normalised to give a value of one at 20 km h^{-1}. The resulting functions are presented in Table C2.

Table C2: Speed correction coefficients *f(V)* and boundaries.

Vehicle category	Pollutant	Correction coefficient *f(V)*	Boundary speed (km h^{-1})
Petrol non-catalyst cars	CO_2	-0.0101*V* + 1.2024	*V*<119
	CO	0.0288*V* + 0.4245	-
	HC	0.0142*V* + 0.7154	-
	NO_x	0.1136*V* - 1.2727	*V*>11
	FC	0.0064*V* + 0.8716	-
Diesel non-catalyst cars	CO_2	1	-
	CO	-0.0185*V* + 1.3704	*V*<74
	HC	-0.0163*V* + 1.3252	*V*<81
	NO_x	-0.0227*V* + 1.4545	*V*<64
	FC	1	-
Petrol catalyst cars	CO_2	0.0034*V* + 0.9321	-
	CO	-0.0013*V* + 1.0261	-
	HC	-0.0053*V* + 1.1060	-
	NO_x	0.0636*V* - 0.2712	*V*>5
	FC	0.0015*V* + 0.9707	-

Effect of ambient temperature

The tests for which results were available covered the start temperature range from -10 to +26°C. In many cases the excess emission tended to increase as the start temperature reduced. Using a simple linear model, functions were determined expressing the excess emission in terms of the start temperature, and were normalised to give a value of one for a start temperature of 20°C. Table C3 gives the results.

Table C3: Temperature coefficients *g(T)* and boundaries.

Vehicle category	Pollutant	Correction coefficient *g(T)*	Boundary temp. (°C)
Petrol non-catalyst cars	CO_2	1	-
	CO	-0.0918*T* + 2.8360	*T*<30
	HC	-0.1344*T* + 3.6888	*T*<27
	NO_x	1	-
	FC	-0.0431*T* + 1.8618	*T*<43
Diesel non-catalyst cars	CO_2	-0.0458*T* + 1.9163	*T*<41
	CO	-0.0602*T* + 2.2048	*T*<36
	HC	-0.0976*T* + 2.9512	*T*<30
	NO_x	-0.0893*T* + 2.7857	*T*<31
	FC	-0.0439*T* + 1.8787	*T*<42
Petrol catalyst cars	CO_2	1	-
	CO	-0.2591*T* + 6.1829	*T*<23
	HC	-0.1317*T* + 3.6331	*T*<27
	NO_x	1	-
	FC	-0.0555*T* + 2.1092	*T*<38

As there are very few data relating to intermediate starting temperatures, it was assumed that the effect of starting when the engine temperature is higher than the ambient temperature is equivalent to a cold start at the temperature of the engine. However, the boundary conditions in the emission-temperature relationships preclude the use of engine start temperatures greater than, at best, 43°C (the intercept on the *x*-axis).

Effect of distance travelled

Only when a vehicle has fully warmed up will its emissions stabilize, and it is necessary to travel a certain distance (the 'cold distance') before that condition is reached. The distance needed varies according to the vehicle type and the pollutant, as well as the way the car is driven (here represented by the average speed).

The cold distance will probably also vary with the ambient temperature, but data are not available to quantify any effect so it has been neglected. Excess emissions are produced during the whole of the cold distance. Any trips shorter than that distance will not, therefore, produce the total amount of excess emission that would result from a longer trip under the same conditions.

Figure C1 shows this principle schematically. Clearly, when the trip distance is equal to the cold distance, the function is equal to one. An exponential function of this form gives a good fit to most of the available data showing the evolution of the excess emission with distance travelled. Naturally, any trips equal to or longer than the cold distance will produce the total excess emission.

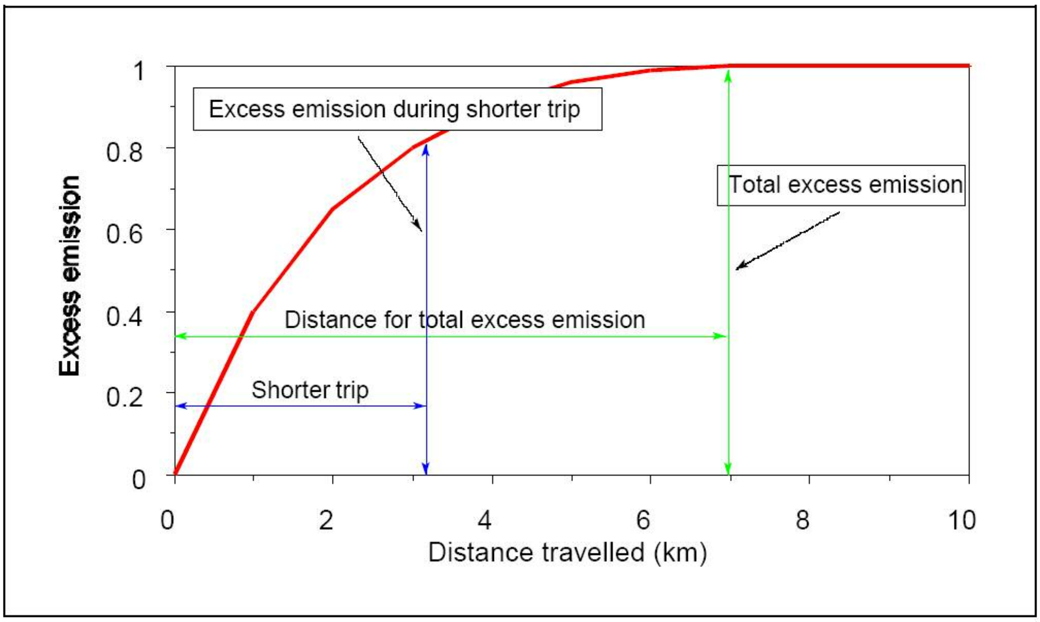

Figure C1: Schematic representation of the effect of trip length on the excess emission.

Corrections to excess emissions for trips shorter than the cold distance are expressed as a function of the quotient of the trip length and the cold distance, thus:

$$\text{Distance correction} = \frac{(1-e^{-a\delta})}{(1-e^{-a})}$$ Equation C2

where:

δ = the quotient of the trip distance and the cold distance
a = a constant

Functions to estimate the cold distance, and the values of a, are given in Table C4.

Table C4: Cold distance d_c as a function of average speed V (km h^{-1}), and values of a.

Vehicle category	Pollutant	Cold distance d_c	Coefficient a
Petrol non-catalyst cars	CO_2	$0.15V + 2.68$	2.85
	CO	$0.04V + 5.42$	6.70
	HC	$0.09V + 1.94$	10.96
	NO_x	$0.02V + 2.83$	2.54
	FC	$0.28V + 0.47$	7.97
Diesel non-catalyst cars	CO_2	$0.24V + 0.09$	3.95
	CO	$0.08V + 4.83$	3.43
	HC	$0.08V + 4.83$	2.48
	NO_x	$-0.07V + 7.50$	0.89
	FC	$0.13V + 3.42$	11.46
Petrol catalyst cars	CO_2	$0.29V -0.05$	3.01
	CO	$0.24V - 0.14$	10.11
	HC	$0.06V + 2.19$	7.02
	NO_x	$0.19V + 3.4$	2.30
	FC	$0.24V + 0.54$	7.55

Other vehicle types

Diesel passenger cars with catalysts

A few results were obtained from tests on diesel cars with catalysts, but they were too limited to allow a detailed analysis. They were, however, used to indicate the reference excess emission (w) for this type of vehicle, and values are included in Table C1. Until additional data are available, it is necessary to assume that the functions *f(V), g(T)* and *h(d)* are the same as those derived for non-catalyst diesels.

Light goods vehicles

Because no data are available for light goods vehicles, it is proposed that their excess emissions should be calculated in the same way as those of passenger cars with the same types of engine and emission control system.

Heavy goods vehicles

There were very few relevant data for this type of vehicle. Nevertheless, it was possible to give a rough estimate of their excess emissions, based on the analysis of results from tests on ten heavy-duty engines. Tests were performed on an engine dynamometer, using the US heavy duty transient tests cycle. They were carried out with a cold engine (approximately 20^{o}C start temperature) and repeated with a hot start. The coolant temperature was monitored during the measurements, and was found typically to reach the hot start value after 600 to 800 seconds from a cold start: the total test duration was 1,200 seconds. It may be assumed therefore that the tests included the whole of the cold-start period, and that the difference between the emissions from the hot and cold tests gives a measure of the cold excess emission. Because the measurements only used one operating cycle and were only performed at one ambient temperature it is not possible to determine whether the excess emission depends on those parameters, as is the case for passenger cars.

The engines varied in cylinder capacity from 3.8 to 14 litres, and their power outputs from 79 to 370 bhp. An analysis of vehicle specification data showed a good correlation between engine power and the gross weight of vehicles, so it was possible to classify these engine data according to the vehicle weight classification adopted for heavy goods vehicles. However, only for CO_2 and NO_x was there any systematic relationship between engine or vehicle size and the excess emission. The results of this exercise are given in Table C5, which lists excess emissions in grammes per cold start for the main regulated pollutants and the four classes of HGV used in the MEET classification system. Note that NO_x emissions from cold-start tests were lower than corresponding hot start emissions and the excess emission is therefore negative.

Operational data for HGVs giving the number of cold starts per day (or other time period) are not known. It is proposed, therefore to assume that each vehicle makes one cold start per day. This assumption is made on the basis that the commercial use of HGVs is likely to mean that they are started from cold at the beginning of each working day, and then used throughout the day without being stopped for long enough to cool significantly. Some vehicles will make more than one cold start per day, but during weekends and holidays, some vehicles will not be used at all.

Table C5: Cold excess emissions for HGVs.

Gross vehicle weight (tonnes)	Cold-start emission by pollutant (g/start)				
	CO_2	CO	HC	NO_x	PM
3.5-7.5	200	6	2	-1	0.6
7.5-16	300	6	2	-2	0.6
16-32	500	6	2	-5	0.6
32-40	750	6	2	-7	0.6

<u>Buses and coaches</u>

Buses and coaches are powered normally by diesel engines of the type discussed above. The cold excess emissions may therefore be assumed to be the same as for HGVs of the same weight class. While there are significant variation in the weights of buses and coaches, depending on their size and seating capacity, the most common weight class is probably 16 to 32 tonnes. In the absence of precise information, it can again be assumed that each vehicle makes one cold start per day.

Appendix D: ARTEMIS methodology (cars)

In the ARTEMIS project, a new cold-start emission calculation approach for cars has been produced by INRETS (André and Joumard, 2005). The general model - which is essentially a refinement of the MEET approach - is a function of ambient temperature, average speed, travelled distance and parking duration. In fact, three different models were developed to calculate cold-start excess emissions from the types of information available to the user:

(i) Excess cold-start emission per start.

(ii) Excess cold-start emission from traffic.

(iii) Aggregated cold-start emission factors.

These three models are described below.

Model 1: excess emission per start

This model gives an excess emission per start (in grammes) for a given vehicle type (*i.e.* combination of fuel type and emission standard) and pollutant, as a function of the ambient temperature T, the mean speed during the cold period V, the travelled distance d, and the parking time t:

$$E_{cold}(T,V,\delta,t) = \omega_{20°C,\,20\,km/h} \cdot f(T,V) \cdot h(\delta) \cdot g(t) \qquad \text{(Equation D1)}$$

where:

E_{cold}	=	Excess emission per start (g).
T	=	Ambient temperature (°C).
V	=	Mean speed during the trip (km h^{-1}).
δ	=	Dimensionless distance = d/d_c (T,V).
d	=	Distance travelled (km).
d_c	=	Cold distance (km).
$\omega_{20°C,20km/h}$	=	Reference excess emission (at 20°C and 20 km h^{-1}).
$f(T,V)$	=	Dimensionless function for speed (V) and temperature (T) effects.
$h(\delta)$	=	Distance effect.
$g(t)$	=	% of excess emission at 12 hours of parking as a function of the parking time t.
t	=	Parking time (h).

The values of d_c, $\omega_{20°C,20km/h}$ and $f(T,V)$ are available for each pollutant. The functions in Table D1 describe the cold distance d_c as a function of the average speed V (km/h) and the temperature T (°C). The results of these functions must be positive.

The functions in Table D2 describe the influence of the mean speed V (km/h) and the ambient temperature T (°C) on the reference excess emission ω (g) and the associated dimensionless correction coefficients f.

The parameter h is an exponential function of δ, and is expressed as:

$$h(\delta) = \frac{1 - e^{a.\delta}}{1 - e^{a}}$$

where a is deduced from the data. The values of a are given in Table D3.

To take into account parking duration, which influences the start engine temperature, data from EMPA (Schweizer *et al.*, 1997), TUG (Hausberger, 1997) and VTI (Hammarström, 2002) were used to derive polynomial functions for each type of car and each pollutant (Table D4). Values for $h(\delta)$ and $g(t)$ are not available for individual hydrocarbon compounds. For these, the functions h and g for total hydrocarbons are used.

Table D1: Cold distance as a function of the average speed and temperature (passenger cars).

Pollutant	Emission standard	Fuel type	$d_c(T,V)$ (km)
CO	Pre-Euro 1, no cat.	Diesel	10.17 - 0.167*T - 0.049*V
		Petrol	2.826 + 0.116*V
	Pre-Euro 1, with cat.	Petrol	1.639 - 0.019*T + 0.054*V
	Euro 1	Diesel	9.553 - 0.042*V
		Petrol	8.805 - 0.132*V
	Euro 2	Diesel	4.916 - 0.039*T + 0.091*V
		Petrol	4.409 - 0.002*T + 0.024*V
	Euro 3	Diesel	4.891 + 0.078*V
		Petrol	4.284 - 0.025*T - 0.004*V
	Euro 4	Petrol	6.716 - 0.06*T
CO_2	Pre-Euro 1, no cat.	Diesel	-2.27 + 0.321*V
		Petrol	2.807 - 0.024*T + 0.141*V
	Pre-Euro 1, with cat.	Petrol	2.172 + 0.126*V
	Euro 1	Diesel	3.474 + 0.163*V
		Petrol	3.838 + 0.081*V
	Euro 2	Diesel	4.31 - 0.04*T + 0.125*V
		Petrol	4.048 - 0.124*T + 0.145*V
	Euro 3	Diesel	9.093 - 0.064*V
		Petrol	2.461 - 0.057*T + 0.173*V
	Euro 4	Petrol	5.398 - 0.142*T
HC	Pre-Euro 1, no cat.	Diesel	6.834 + 0.022*V
		Petrol	3.578 - 0.052*T + 0.093*V
	Pre-Euro 1, with cat.	Petrol	2.087 - 0.042*T + 0.099*V
	Euro 1	Diesel	3.444 + 0.226*V
		Petrol	7.972 - 0.048*V
	Euro 2	Diesel	4.79 - 0.021*T + 0.116*V
		Petrol	5.201 - 0.037*T + 0.065*V
	Euro 3	Diesel	7.341 + 0.07*V
		Petrol	3.552 - 0.092*T + 0.135*V
	Euro 4	Petrol	6.97 - 0.16*T
NO_x	Pre-Euro 1, no cat.	Diesel	3.18 + 0.087*V
		Petrol	2.879 + 0.081*V
	Pre-Euro 1, with cat.	Petrol	1.92 - 0.026*T + 0.101*V
	Euro 1	Diesel	-4.392 + 0.317*V
		Petrol	4.318 - 0.016*V
	Euro 2	Diesel	0.76 - 0.033*T + 0.158*V
		Petrol	-2.515 + 0.238*V
	Euro 3	Diesel	9.809 - 0.094*V
		Petrol	1.922 + 0.091*V
	Euro 4	Petrol	4.523

Table D2: Equation of the cold start excess emission ω and the correction coefficient f (passenger cars).

Pollutant	Emission standard	Fuel type	Excess emission ω	Correction coefficient f
CO	Pre-Euro 1, no cat.	Diesel	5.102 -0.044*T -0.074*V	1.851 -0.016*T -0.027*V
		Petrol	129.521 -5.361*T + 1.285*V	2.698 -0.112*T + 0.027*V
	Pre-Euro 1, with cat.	Petrol	128.022 -5.731*T + 0.126*V	8.044 -0.36*T + 0.008*V
	Euro 1	Diesel	4.662 -0.067*T -0.061*V	2.198 -0.031*T -0.029*V
		Petrol	30.369 -1.221*T + 0.437*V	2.068 -0.083*T + 0.03*V
	Euro 2	Diesel	7.711 -0.199*T -0.05*V	2.824 -0.073*T -0.018*V
		Petrol	32.873 -0.74*T -0.051*V	1.927 -0.043*T -0.003*V
	Euro 3	Diesel	2.455 -0.02*V	1.194 -0.01*V
		Petrol	35.45 -1.455*T + 0.096*V	4.291 -0.176*T + 0.012*V
	Euro 4	Petrol	31.627 -1.338*T	6.488 -0.274*T
CO_2	Pre-Euro 1, no cat.	Diesel	854.4 -17.56*V	1.698 -0.035*V
		Petrol	214.922 -6.528*T -0.088*V	2.602 -0.079*T -0.001*V
	Pre-Euro 1, with cat.	Petrol	133.024-0.306*V	1.048-0.002*V
	Euro 1	Diesel	374.171 -8.405*T -2.606*V	2.43 -0.055*T -0.017*V
		Petrol	162.937 -5.435*T + 0.358*V	2.654 -0.089*T + 0.006*V
	Euro 2	Diesel	362.34 -10.921*T -0.14*V	2.567 -0.077*T -0.001*V
		Petrol	194.662 -3.546*T + 0.504*V	1.454 -0.026*T + 0.004*V
	Euro 3	Diesel	171.52-0.381*V	1.047-0.002*V
		Petrol	186.055 -5.365*T + 2.283*V	1.496 -0.043*T + 0.018*V
	Euro 4	Petrol	168.005 -5.165*T	2.597 -0.08*T
HC	Pre-Euro 1, no cat.	Diesel	1.607-0.028*V	1.538-0.027*V
		Petrol	27.712 -1.278*T + 0.233*V	4.068 -0.188*T + 0.034*V
	Pre-Euro 1, with cat.	Petrol	10.853 -0.439*T + 0.035*V	3.893 -0.157*T + 0.013*V
	Euro 1	Diesel	0.75 -0.007*T -0.011*V	1.835 -0.016*T -0.026*V
		Petrol	8.653 -0.114*V	1.357 -0.018*V
	Euro 2	Diesel	2.38 -0.094*T -0.006*V	6.247 -0.247*T -0.015*V
		Petrol	6.997 -0.059*T -0.071*V	1.597 -0.014*T -0.016*V
	Euro 3	Diesel	0.129 + 0.001*V	0.863 + 0.007*V
		Petrol	8.229 -0.415*T + 0.049*V	9.093 -0.459*T + 0.054*V
	Euro 4	Petrol	5.184 -0.247*T	21.246 -1.012*T
NO_x	Pre-Euro 1, no cat.	Diesel	-0.489 + 0.015*V	2.472 -0.074*V
		Petrol	0.934 -0.036*T -0.017*V	-7.182 + 0.276*T + 0.133*V
	Pre-Euro 1, with cat.	Petrol	2.159 -0.094*T + 0.023*V	2.894 -0.126*T + 0.031*V
	Euro 1	Diesel	2.281 -0.098*T -0.017*V	-120.03 + 5.171*T + 0.881*V
		Petrol	0.053 + 0.04*V	0.063 + 0.047*V
	Euro 2	Diesel	1.686 -0.082*T + 0.002*V	20.076 -0.978*T + 0.024*V
		Petrol	0.287 + 0.021*V	0.406 + 0.03*V
	Euro 3	Diesel	-0.909 + 0.04*V	8.335 -0.367*V
		Petrol	0.282 -0.002*T + 0.005*V	0.808 -0.005*T + 0.015*V
	Euro 4	Petrol	0.186	1

Table D3: Values of the coefficient *a* in the equation of the dimensionless cold start excess emission *h* (passenger cars).

Pollutant	Emission standard	Fuel type	*a*
CO	Pre-Euro 1, no cat.	Petrol	-3.050
	Pre-Euro 1, with cat.	Diesel	-6.066
		Petrol	-5.579
	Euro 1	Diesel	-3.083
		Petrol	-4.533
	Euro 2	Diesel	-6.731
		Petrol	-9.007
	Euro 3	Diesel	-9.503
		Petrol	-7.280
	Euro 4	Petrol	-5.544
CO_2	Pre-Euro 1, no cat.	Petrol	-3.432
	Pre-Euro 1, with cat.	Diesel	-2.330
		Petrol	-2.680
	Euro 1	Diesel	-4.078
		Petrol	-2.714
	Euro 2	Diesel	-3.767
		Petrol	-2.563
	Euro 3	Diesel	-3.389
		Petrol	-3.662
	Euro 4	Petrol	-2.686
HC	Pre-Euro 1, no cat.	Petrol	-3.352
	Pre-Euro 1, with cat.	Diesel	-5.204
		Petrol	-10.737
	Euro 1	Diesel	-3.242
		Petrol	-8.923
	Euro 2	Diesel	-4.388
		Petrol	-10.209
	Euro 3	Diesel	-12.140
		Petrol	-8.624
	Euro 4	Petrol	-11.898
NO_X	Pre-Euro 1, no cat.	Petrol	-2.926
	Pre-Euro 1, with cat.	Diesel	-2.615
		Petrol	-2.246
	Euro 1	Diesel	-1.776
		Petrol	-5.752
	Euro 2	Diesel	-4.729
		Petrol	-3.765
	Euro 3	Diesel	-2.479
		Petrol	-0.739
	Euro 4	Petrol	-0.432

Table D4: Equations describing the parking time influence on the cold start excess emission on passenger cars. The parking time *t* is in minutes (g(720) = 1).

Vehicle type	Pollutant	Equation
Catalyst petrol cars	CO	$g(t) = 4.614*10^{-3}*t-2.302*10^{-6}*t^2 -2.966*10^{-9}*t^3$ ($t \leq 720$) $g(t) = 1$ ($t>720$ min)
	CO_2	$g(t) =0.1349*t-2.915*10^{-4}*t$ ($t \leq 20$) $g(t) = 0.136+0.12*t$ ($21 \leq t \leq 720$) $g(t) = 1$ ($t \geq 720$)
	HC	$g(t) = 7.641*10^{-3}*t-2.639*10^{-5}*t^2 +3.128*10^{-8}*t^3$ ($t \leq 240$) $g(t) = 0.625+5.208*10^{-4}*t$ ($241 \leq t \leq 720$) $g(t) = 1$ ($t \geq 720$)
	NO_x	$g(t) =7.141*10^{-3}*t+1.568*10^{-3}*t^2 -3.204*10^{-5}*t^3+1.594*10^{-7}*t^4$ ($t \leq 50$ min) $g(t) = 1.290-4.030*10^{-4}*t$ ($51 \leq t \leq 720$) $g(t) = 1$ ($t \geq 720$)
Petrol cars without catalyst	CO	$g(t) = -1.504*10^{-2}*t+1.406*10^{-4}*t^2 -2.547*10^{-7}*t^3$ ($t \leq 240$) $g(t) = 1$ ($t>240$ min)
	CO_2	$g(t) =5.287*10^{-9}*t^3-8.864*10^{-6}*t^2 +5.035*10^{-3}*t$ ($t<720$ min) $g(t) = 1$ ($t>720$ min)
	HC	$g(t) = 1.039*10^{-3}*t-7.918*10^{-6}*t^2 +4.211*10^{-8}*t^3-6.856*10^{-11}*t^4 +3.650*10^{-14}*t^5$ ($t \leq 720$) $g(t) = 1$ ($t \geq 720$)
	NO_x	$g(t) = 3.52*10^{-2}**t-3.705*10^{-4}*t^2$ ($t \leq 50$) $g(t) = 0.8170+2.537*10^{-4}*t$ ($51 \leq t \leq 720$) $g(t) = 1$ ($t \geq 720$)
Diesel cars	CO	$g(t) = 4.167*10^{-3}*t$ ($t \leq 240$ min) $g(t) = 1$ ($t \geq 240$ min)
	CO_2	$g(t) = 4.339*10^{-3}*t-4.747*10^{-6}*t^2$ ($t \leq 460$) $g(t) = 0.978+3.077*10^{-5}*t$ ($461 \leq t \leq 715$) $g(t) = 1$ ($t \geq 715$ min)
	HC	$g(t) = 3.070*10^{-4}*t+4.402*10^{-6}*t^2 -4.030*10^{-9}*t^3$ ($t \leq 720$) $g(t) = 1$ ($t>720$ min)
	NO_x	$g(t) = 0$ ($t \leq 300$ min) $g(t) = -1.11+3.703*10^{-3}*t$ (300 min$<t<$570 min) $g(t) = 1$ ($t \geq 570$ min)

Model 2: full model of excess emission of a traffic

In some cases, assessing cold-start emissions for a single trip is sufficient, but most emission inventories require the calculation of cold-start emissions not for a single vehicle and a single trip, but for the whole traffic - characterised by a number of parameters such as traffic flow, average speed, hour of the day, ambient temperature, *etc*.. This is the aim of the second model.

This model gives an excess emission of a traffic in grammes, as a function of:

- Traffic flow
- Season (winter, intermediate, summer, year)
- Average speed
- Ambient temperature
- Hour of the day

Distributions of the distance travelled according to average speed, ambient temperature and parking time are required. Default values are given, but the user can also define the distributions. The ambient temperature, the mean speed and the hour in the day generally play major roles. The season, for a given temperature, is less important.

$$E_c(p) = \sum_i \frac{cm(s,v_i)}{100} \cdot \omega_i(p) \cdot \left[\sum_h tf_{i,h} \cdot \frac{p_h(s)}{ptf_{i,h}} \cdot \left\{ \sum_j \sum_m \sum_n \frac{p_{i,j}(s) \cdot p_{m,j}(s) \cdot p_{n,h}(s)}{10^6 d_m} \cdot f(p,v_j,T) \cdot h(p,\delta(p,T,v_j,d_m)) \cdot g(p,t_n) \right\} \right]$$

(Equation D2)

where:

$E_c(p)$	=	Traffic excess emissions with a cold engine for the pollutant *p* corresponding to traffic $tf_{i,h}$ *(g)*
p	=	Atmospheric pollutant
i	=	Vehicle type
$cm(s,v_i)$	=	% of mileage under cold start or intermediate temperature conditions for season *s* and overall speed v_i of vehicle type *i*
s	=	Season (winter, summer, intermediate, year)
v_i	=	Overall average speed for the vehicle type *i* (km/h)
$\omega_i(p)$	=	Reference excess emission for the vehicle type i and the pollutant *p* (g)
h	=	Hour (1 to 24, day)
$tf_{i,h}$	=	Traffic flow for the studied vehicle type *i* and the hour *h* (km.veh)
p_h	=	Relative cold-start number for the hour h (average=1)
$ptf_{i,h}$	=	Relative traffic flow for the vehicle type *i* and the hour *h* (average=1)
j	=	Speed class with a cold engine
m	=	Trip length class
n	=	Class of stops (0 – 1/4, 1/4 – 1/2, 1/2 – 3/4, 3/4 - 1, 1 - 2,... , >12h)
$p_{i,j}$	=	% of the distance travelled at speed *j* with a cold engine, for the overall average speed, and for the studied vehicle type *i* (%)
$p_{m,j}$	=	% of the distance started with a cold engine and distance d_m, for speed V_j with a cold engine (%)
$p_{h,n}$	=	% of the distance travelled after a stop with a duration of t_n, for the hour *h* (%)
d_m	=	Average distance of the trips under cold-start conditions of class *m* (km)
$f(p,V_j,T)$	=	Plane function of the speed V_j and the temperature *T*, for the pollutant *p*
V_j	=	Average speed with a cold engine corresponding to class *j* (km/h)
T	=	Ambient temperature (°C)
$h(p,\delta)$	=	$(1-e^{a(p,T).\delta})/(1-e^{a(p,T)})$
a(p)	=	Constant coefficient for a pollutant *p*
$\delta(p,T,V_j,d)$	=	Dimensionless distance = $d_m/(d_c(P,_{Vj},T)$
$d_c(p,V_j,T)$	=	cold distance for the pollutant *p* (km)
$g(p,t_n)$	=	% of excess emission at 12h of parking as a function of the parking time t_n for the pollutant *p*
t_n	=	Parking time (*h*)

Amongst all these parameters, different types of parameter can be distinguished:

- Some are purely internal and should not be modified by the user: $\omega_i(p)$, $f(p,V_j,T)$, $d_c(p,V_j,T)$ and $g(p,t_n)$
- Some parameters are input parameters: i, s, v_i, h, tf_{ih}, $ptf_{i,h}$ and T.
- Some parameters are internal parameters, but could be modified by the advanced user: $cm(s,v_i)$, ph, $p_{i,j}$, $p_{m,j}$, $p_{h,n}$, d_m and V_j, $\omega_i(p)$ and $f(p,V_j,T)$ are given for each pollutant p, regulated or unregulated.

Values for $h(p,\delta)$ and $g(p,t_n)$ are not available for the unregulated hydrocarbons. Again, for these components the functions h and g for the total hydrocarbons are used.

According to Duboudin and Crozat (2002), the inclusion of average speed in Equation D2 is problematic, because of the possible difference between the average speed during the cold period and the average speed during the whole trip. A trip with an average speed v_i is subdivided into a cold phase and a hot phase. The cold phase can have an average speed V_j different from the global speed v_i. To calculate the global emission a hot emission, calculated using v_i, is added, and the cold excess emission is calculated using V_j:

$$E_{total}\,(trip) = E_{cold}\,(V_j\,) + E_{hot}\,(v_i) \quad \text{(Equation D3)}$$

If the distance travelled during the cold phase d_c corresponds to an average speed V_j which is different to the speed of the whole trip v_i, the travelled distance under hot conditions cannot have an average speed v_i, and the global emission should be calculated using the formula:

$$E_{total}\,(d_c + d_{hot}\,) = E_{cold}\,(V_j\,,d_c\,) + E_{hot}\,(V_j\,,d_c\,) + E_{hot}(V_{hot}\,,d_{hot}\,) \quad \text{(Equation D4)}$$

where V_{hot} is the average speed of the hot distance d_{hot}.

Model 3: aggregated model of excess unit emission of a traffic

Both the previous two models are not easy to use. The first model needs to be complemented by a model giving the numbers and characteristics of the starts. The second model is the most comprehensive and accurate model, but is especially complex to use, and much of the required information is difficult to obtain. It is possible that the use of this model could give misleading results.

Therefore, a simplified approach was developed, whereby the second model, with all its default values, was executed and the outputs were transformed to give excess cold-start emission factors in mass per unit distance. The input variables are season, ambient temperature, average speed and hour of the day. The result is a series of tables in which the cold-start unit excess emission factors are presented for each vehicle category, each pollutant (CO, CO_2, THC, NO_x, 29 PAHs and 87 VOCs), each season (year, winter, summer and intermediate), hour of the day, ambient temperature and overall traffic mean speed. Each emission factor is multiplied by the traffic activity per vehicle category (in veh.km), and the results are summated to give the total emission factor for the traffic.

The calculation of the third model requires a specific assumption on the relative traffic distribution along the day ($ptf_{i,h}$). Table D5 shows the relative traffic distribution of $ptf_{i,h}$ during the day used in the design of the third model (the ‘base’ distribution shown in Figure D1).

The table of results is given by André and Joumard (2005). The results for unregulated pollutants are available via application to the authors.

However, when applying this model, if the actual traffic distribution is very different from the default distribution, the overall emission calculated during the day can be wrong. For instance, for the average traffic distributions representative of USA, Belgium and Switzerland (Figure D1), the use of the third model introduces an error for the whole day of between 3% and 7%. In such cases, it is recommend that this model is not used on a hourly basis, but that either the second model is used, or model three is used for the whole day - the summation over the day of the hourly cold excess emissions will be more accurate, but its distribution between the hours will not be accurate.

Table D5: Base traffic distribution used in the design of the third could start model.

Hour	$ptf_{i,h}$	Hour	$ptf_{i,h}$
1	0.12	13	1.40
2	0.08	14	1.60
3	0.05	15	1.93
4	0.08	16	2.17
5	0.13	17	1.99
6	0.32	18	1.76
7	1.29	19	1.28
8	1.78	20	0.86
9	1.16	21	0.58
10	1.33	22	0.39
11	1.50	23	0.31
12	1.71	24	0.18

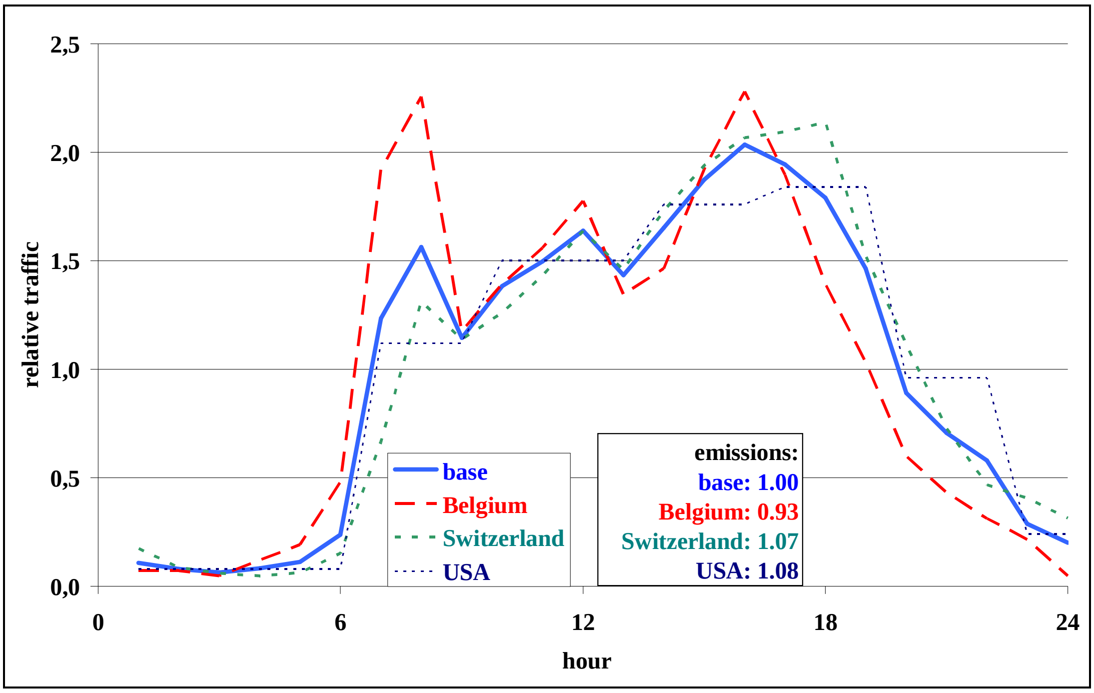

Figure D1: Average traffic distributions representative of 3 countries (relative to the hourly average), and relative base distribution (average) used in the third model design. Relative influence of the using of the different distributions on the daily emissions.

There are clearly a number of limitations of this approach for local applications (Joumard, 2005), and the average values could differ from the actual local values quite considerably. For a single street one problem is that each vehicle does not stay in the street for very long. A portion of the extra cold emission can occur before the vehicle enters the street, or after it leaves the street. Ideally, precise journey statistics are required all the vehicles using the street: how far they travel before entering the street, how far they travel before leaving the street, their start engine temperature, all according to the ambient temperature, the hour, *etc*. If a user is allowed to modify the various statistical information required, he or she is usually unable to verify their consistency. This makes the accurate modelling of local cold-start emissions extremely difficult.

Appendix E: PHEM approach

A cold-start modelling approach for cars and HDVs based on a heat balance of the engine and the exhaust gas line has been proposed by Engler *et al.* (2001) for use in PHEM. Rexeis *et al.* (2005) describe the construction of PHEM for the modelling of hot exhaust emissions from HDVs, and Zallinger *et al.* (2005) describe its application to passenger cars.

After building and testing the model for hot exhaust emissions, PHEM was extended to simulate cold-start emissions. The cold-start work initially focussed on passenger cars, with particular emphasis being given to the design of the method so that it would be valid for any driving condition and any ambient temperature (Engler *et al.*, 2001). The need for detailed input information means that the model is not particularly well suited to direct use in emission inventory applications, but could be used to generate appropriate emission factors. The simulation of average cold-start emissions from passenger cars and light duty vehicles with petrol and diesel engines was reported by Zallinger *et al.* (2005), but definitive values are not given.

The cold-start model is based upon the assumption that the excess emissions during a cold start can be expressed in terms of the temperatures of relevant components. Equation E1 shows the general form of the relationship between cold-start and hot exhaust emissions.

$$E_{cold} = E_{hot} + f(\delta_{coolant}, \delta_{oil}, \delta_{cat}) \qquad \text{Equation E1}$$

where: E_{cold} = emissions before reaching operating temperature (g/h)
E_{hot} = emissions at operating temperature (g/h)
δ = temperature of the component (coolant, oil and catalyst)

Figure E1 illustrates the heat balance. The heat sources are the energy content of the fuel and, when the catalyst light-off temperature has been reached, exothermic reactions in the catalyst. The heat is transferred into the different components and then to the ambient air.

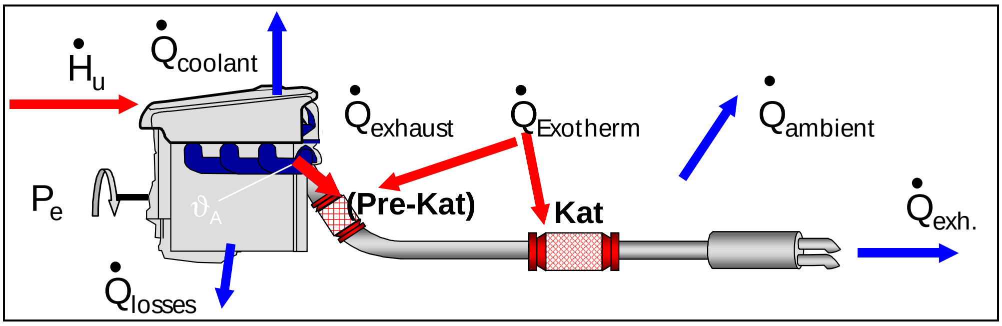

Figure E1: Heat balance in the engine and the exhaust system (Engler *et al.*, 2001).

If the full operating temperatures are not reached, the system is not stationary and some of the heat is used for increasing the temperatures of the components. Equation E2 shows the detailed heat balance.

$$\dot{H}_u - Pe = \dot{Q}_{exhaust} + \dot{Q}_{coolant} + Q_{amb} + \sum A_i \times m_i \times c_i \times \frac{d\delta_i}{dt} \qquad \text{Equation E2}$$

where:

$\dot{H}_u$ = fuel consumption per second (lower heating value/s)

$\dot{Q}_{exhaust}$ = heat flux of exhaust gas

$\dot{Q}_{coolant}$ = heat flux into the coolant

$\dot{Q}_{amb}$ = heat flux into the ambient air

$\frac{d\delta_i}{dt}_i$ = differential temperature increase of a pollutant *i*.

For the detailed simulation of these processes many parameters have to be known (*e.g.* specific thermal capacities, heat transfer coefficients). Therefore, the heat balance was simplified in PHEM, as shown in Equation E3.

$$\boldsymbol{\delta_i = F\left(\int_{t=0}^{t=n}((\dot{H}u_i - Pe_i)dt\right)} \qquad \text{Equation E3}$$

where:

δ_i = temperature of a component at *n* seconds after cycle start

$(\dot{H}u_i - Pe_i)$ = difference between energy content of the fuel and useful power output of the engine per second (“heat loss”)

Equation E3 is derived from Equation E2 using the basic simplification that the share of heat loss flowing into each component is independent of the actual engine load. The temperature curves (coolant, catalyst) measured for different driving cycles are very similar if plotted against cumulative heat loss (Figure E2).

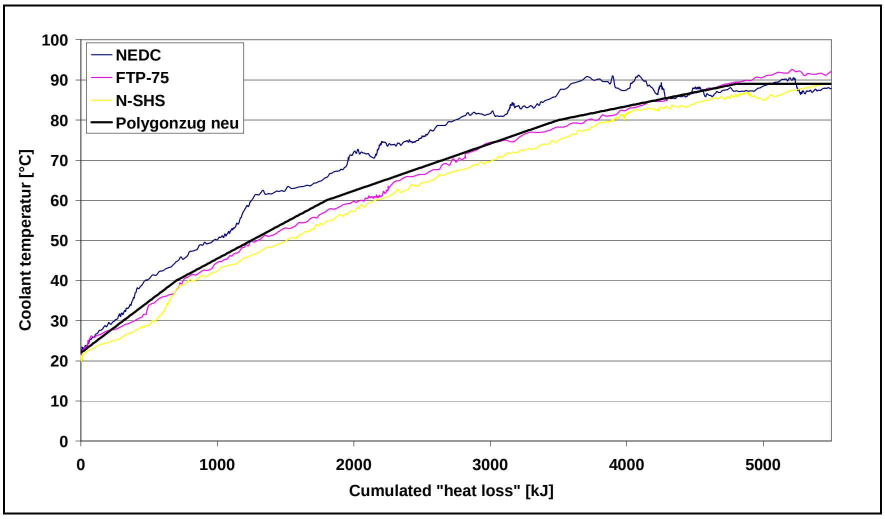

Figure E2: Measured temperature of the coolant of a passenger car during three different cycles as function of the cumulative heat loss (Engler *et al.*, 2001).

Since the simplified heat balance gives reliable results independent of the driving cycle measured, for the simulation the measured temperature curves over the cumulative heat loss are replaced by average curves for each vehicle category. The heat loss can be obtained from the hot emission model in PHEM, which calculates the actual power demand and the fuel consumption every second during a driving cycle. The cold-start fuel consumption value is calculated for this task based on the coolant temperature.

As the model is capable of simulating the temperatures of the coolant, the oil and – in case of passenger cars – the catalytic converter, the main task is finding functions which express the emissions under cold-start conditions from the temperatures of the components. For HDVs a simple approach is used, whereby the ratio of the emissions after a cold start to the emissions under hot operating conditions is calculated from measurements on the chassis dynamometer as a function of the coolant temperature during the cold start. For passenger cars equipped with a 3-way catalytic converter more sophisticated methods are required (Engler *et al.*, 2001).

Emission factors 2009: Report 4 – a review of methodologies for modelling cold-start emissions

TRL was commissioned by the Department for Transport to review the approach used in the National Atmospheric Emissions Inventory (NAEI) for estimating emissions from road vehicles, and to propose new methodologies. This Report summarises the models which are available for estimating "cold-start" emissions. Exhaust emissions of regulated pollutants are higher during the cold-start phase than when the engine, lubricants, coolants, exhaust catalyst, drive train and tyres are at their design temperatures. This is due to a combination of incomplete fuel combustion in the engine, catalyst inefficiency, and increased friction in the engine and drive train and at the tyre-road interface. A wide range of factors affect cold-start emissions, and the Report includes a brief summary of a number of studies dealing with the subject. The method used in the NAEI for estimating cold-start emissions is summarised, and potential limitations are highlighted. The Report also identifies a number of potential sources of data which might be used to update and refine the modelling approach in the NAEI. The main conclusion of the Report is that before any more detailed modelling of cold-start emissions is attempted the current NAEI model (which is based upon the COPERT II model) should be updated to reflect the COPERT 4 methodology. However, new methodologies are scheduled to be available in 2009, and when these are published they should be considered for inclusion in the NAEI.

Other titles from this subject area

PPR270 Scoping study on the potential for instantaneous emission modelling: summary report. T J Barlow, P G Boulter and I S McCrae. 2007

PPR269 The links between micro-scale traffic, emission and air pollution models. P G Boulter and I S McCrae. 2007

PPR268 An evaluation of instantaneous emission models. T J Barlow, P G Boulter and I S McCrae. 2007

PPR267 A review of instantaneous emission models for road vehicles. P G Boulter, I S McCrae and T J Barlow. 2007

PPR262 Primary NO_2 emissions from road vehicles in the Hatfield and Bell Common Tunnels. P G Boulter, I S McCrae and J Green. 2007

PPR216 An innovative dynamometer: free running rollers to provide a potential cheap representative roadside emission procedure. S Latham. 2007

Price code: 3X

ISSN 0968-4093

TRL
Crowthorne House, Nine Mile Ride
Wokingham, Berkshire RG40 3GA
United Kingdom

T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

Published by

IHS
Willoughby Road, Bracknell
Berkshire RG12 8FB
United Kingdom

T: +44 (0) 1344 328038
F: +44 (0) 1344 328005
E: trl@ihs.com
W: http://emeastore.ihs.com

ISBN 978-1-84608-818-6

9 781846 088186

PPR357