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Emission factors 2009: Report 7 – a review of the NAEI methodology for modelling evaporative emissions

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Emission factors 2009: Report 7 - a review of the NAEI methodology for modelling evaporative emissions

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Prepared for: **Department for Transport, Cleaner Fuels & Vehicles 4**
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Executive Summary

TRL Limited was commissioned by the Department for Transport to review the methodology used in the National Atmospheric Emissions Inventory (NAEI) for estimating emissions from road vehicles. Various aspects of the methodology were addressed.

This Report presents a review of methodologies and models for estimating evaporative emissions of volatile organic compounds (VOCs), and provides recommendations for the NAEI methodology.

Evaporative emissions constitute a significant fraction of total VOCs emitted from road transport. Most evaporative emissions emanate from the fuel systems (tanks, injection systems and fuel lines) of petrol vehicles. Evaporative emissions from diesel vehicles are considered to be negligible due to the low volatility of diesel fuel. The Report deals with three mechanisms by which petrol fuel evaporates from vehicles:

- Diurnal emissions
- Hot-soak emissions
- Running emissions

The NAEI data and methodologies are rather old and are due for revision. The NAEI approach for evaporative emissions is based largely on the COPERT II and COPERT III models, combined with supporting experimental data from before 1995. However, until recently few new measurements of evaporative emissions had been conducted in Europe, and therefore models had not been updated. The most significant recent measurements and model developments have been the following:

- The European Commission's Fifth Framework project ARTEMIS.
- A EUCAR/JRC/CONCAWE joint programme on evaporative emissions from petrol cars.
- The release of a draft update (version IV) of COPERT. COPERT 4 takes into account the ARTEMIS and EUCAR/JRC/ CONCAWE work.

Comparisons between the NAEI, ARTEMIS and draft COPERT 4 models are described in the Report, and the results from the EUCAR/JRC/CONCAWE research programme are summarised.

All three models showed that vehicles without evaporative emission-control systems exhibit substantially higher diurnal emissions than controlled vehicles. However, the majority of vehicles on UK roads now contain such controls, and therefore uncontrolled emissions are gradually becoming less important as these vehicles are phased out.

All three models use a different system of vehicle categorisation, with ARTEMIS and COPERT 4 providing more detail than the NAEI model. This allows more in-depth assessments to be made, and allows the reasons for differences in total emissions to be better understood. The NAEI method could therefore be further refined by introducing a more detailed vehicle classification system for evaporative emissions.

The total fleet-weighted annual emission factors in the three models are rather similar, ranging from around 2.5 kg vehicle^{-1} year^{-1} to around 3 kg vehicle^{-1} year^{-1}. This is in spite of the fact that the relative contributions of diurnal, hot soak and running emissions in the three models are very different. In particular, running emissions in the NAEI, and diurnal emissions in COPERT 4, are very low compared with the other models.

In view of the large discrepancies between the predictions of running and diurnal emissions, there is a case for examining these sources in more detail and, if necessary, performing further validation tests. It is also noted that vehicles which have failures in the evaporative emissions-control system are classed as having pre-Euro 1 evaporative emission levels in the ARTEMIS model. Although failures were not specifically addressed in this work it is more likely that failures are partial, and that this assumption is too severe.

The main conclusion of this work is that, given that considerable effort has be put into developing the new method in COPERT 4 and the flexibility it offers, there would be sufficient justification for changing the NAEI to include this method. This Report has only examined the simplified 'Tier 2' version of COPERT 4. Further work is required to assess the applicability and reliability of the detailed 'Tier 3'method in COPERT 4. This work was considered to be beyond the scope of this report.

Allowance should also be made in the NAEI for the failure of evaporative control systems. Again, the detailed method of COPERT 4 allows for this. However, there is little or no information on the actual proportion of in-service vehicles in the UK which have failures. This is also an area which requires further investigation.

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 reduce UK emissions. Projections from the road transport model in the NAEI are used to assess the potential benefits of policies and future emission standards for new vehicles. It is therefore essential that the model is as robust as possible and is based on sound data.

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

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

- Task 1: Review of the methods used to measure hot exhaust emission factors, including test cycles and data collection methods (Boulter *et al.*, 2009).
- Task 2: Review of the use of average vehicle speed to characterise hot exhaust emissions (Barlow and Boulter, 2009).
- Task 3: Development of new emission factors for regulated and non-regulated pollutants (Boulter *et al.*, 2009b).
- Task 4: Review of cold-start emissions modelling (Boulter and Latham, 2009b).
- Task 5: Reviewing the effects of fuel quality on vehicle emissions (Boulter and Latham, 2009b).
- Task 6: Review of deterioration factors and other modelling assumptions (Boulter, 2009).
- Task 7: Review of evaporative emissions modelling (this Report).
- 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 7 - a review of methodologies and models for estimating evaporative emissions[2] of volatile organic compounds (VOCs). The aims of the Report are to check the validity of the NAEI method for current vehicles and fuel specifications, and to provide recommendations for the inventory methodology.

Chapter 2 provides some background information on evaporative emissions. The method used in the NAEI to determine evaporative emissions is described in Chapter 3. The NAEI data and methodologies are rather old and are due for revision. However, until recently few new measurements of evaporative emissions had been conducted in Europe, and therefore models had not been updated. The most significant recent measurements and model developments have been the following:

- The European Commission's Fifth Framework project ARTEMIS. The measurements and modelling work which were conducted in ARTEMIS are described in Chapter 4.
- The EUCAR/JRC/CONCAWE joint programme on evaporative emissions from petrol cars (Martini *et al.*, 2007). The objectives of this study were to investigate the impacts of the addition of ethanol to petrol on evaporative emissions from cars, and to provide revised and validated emission factors for evaporative emissions. A large experimental programme has been carried out at JRC, with CONCAWE and EUCAR having provided the test fuels and cars. The final report was published in 2007.

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

[2] In the context of evaporation, emissions are sometimes referred to as 'losses'.

- The release of a draft update (version 4) of COPERT (COmputer Programme to calculate Emissions from Road Transport). COPERT 4 takes into account the ARTEMIS and EUCAR/JRC/ CONCAWE work, and the proposed methodology for COPERT 4 is given in Chapter 5.

Comparisons between the NAEI, ARTEMIS and draft COPERT 4 models are described in Chapter 6, and the results from the EUCAR/JRC/CONCAWE research programme are summarised in Chapter 7. The conclusions and recommendations from the work are given in Chapter 8.

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.

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

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

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

2 Evaporative emissions

2.1 Background

Evaporative emissions of VOCs constitute a significant fraction of total VOCs emitted from road transport. Barlow (1993) estimated that 45% of VOC emissions derived from road vehicles in the UK were produced by evaporation. More recently, data for the 2004 NAEI[5] indicate that the corresponding proportion is around 19%. However, evaporative emissions of VOCs from road transport in 2004 were only responsible for around 2% of total emissions of VOCs in the UK.

Several hydrocarbon compounds are associated with direct health effects, and also contribute, via chemical reactions with NO_x in the presence of sunlight, to the formation of photochemical smog. Evaporative emissions are almost exclusively a summer problem due to their sensitivity to ambient temperature. It is on hot, sunny days, when ozone levels are the highest, that evaporative emissions can account for the majority of the vehicle-derived VOC emissions. Concerns regarding the control of evaporative emissions have grown over the years as exceedences of the health-based ozone standard have continued to be a problem in many areas (Hausberger *et al*., 2005).

Prior to 1993 evaporative losses from petrol passenger cars were not controlled in European countries, with the exception of Austria, Denmark, Finland, Sweden and Switzerland which adopted the US test procedure. In the European Union, a limit value of 2.0 grammes of HC per test was first introduced by Directive 91/441/EEC (Euro 1 and Euro 2 vehicles). In order to meet this emission limit, the installation of small on-board carbon canisters was necessary. Directive 91/441/EC was superseded by Directive 98/69/EC, applicable to Euro 3 and Euro 4 vehicles. The limit value for evaporative emissions remained at the same level, but the evaporative emissions testing procedure increased in severity. The introduction of larger carbon canisters was necessary to comply with these more stringent requirements.

In spite of the tightening of emission standards, improvements in vehicle technology, and petrol regulations, the problem of evaporative emissions remains. This is mainly due to the continuing presence of older, uncontrolled vehicles, vehicles with defective evaporative control systems, motorcycles and a variety of recreational vehicles (Hausberger *et al*., 2005).

2.2 Sources of evaporative emissions

Most evaporative emissions of VOCs emanate from the fuel systems (tanks, injection systems and fuel lines) of petrol vehicles. Evaporative emissions from petrol vehicles consist mainly of light hydrocarbons (C_4 to C_6) (CONCAWE, 1987). Evaporative emissions from diesel vehicles are considered to be negligible due to the presence of heavier hydrocarbons and the extremely low volatility of diesel fuel.

There are five mechanisms by which petrol fuel evaporates from vehicles, and these are described below (Hausberger *et al*., 2005).

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

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

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

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

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

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

2.3 Factors affecting evaporative emissions

The earliest studies of the effects of different factors on evaporative emissions were conducted in the United States in the 1960s (Wade, 1967). The first European studies were conducted twenty years later on ‘uncontrolled’ vehicles, conventional fuels and early-model carbon-canister-equipped cars (CONCAWE, 1987, 1988 and 1990), and most of the available data for modelling were obtained from these studies.

According to Hausberger *et al*. (2005), evaporative emissions from motor vehicles are dependent upon four major factors:

- The vehicle and fuel system design (including any control system for evaporative emissions).
- The ambient temperature and its temporal variation.
- The petrol volatility - usually expressed by the empirical fuel parameter known as Reid vapour pressure (RVP).
- Driving conditions (trip length, parking time, *etc.*).

Barlow (1993) found that diurnal emissions tend to increase with both vehicle size (*i.e.* engine size, vehicle weight, and fuel tank capacity) and age. The factors affecting diurnal emissions appeared to have little effect on hot-soak emissions. It was suggested that many factors could lead to the variations in the evaporative emissions from different vehicles, including differences in the fuel and carburation, and faulty components.

2.4 Control of evaporative emissions

Evaporative emissions are not easily controlled due to the fact that venting of the vehicle tank system must be provided so it can ‘breathe’ during temperature changes. In the past, fuel vapours were simply vented into the atmosphere. Nowadays, the control of evaporative emissions can be achieved via the control of fuel properties and by vehicle technology. These two aspects are discussed briefly below.

2.4.1 Fuel properties

The fuel standard in Europe for vehicles equipped with spark-ignition engines was originally defined in Directive 98/70/EC. This introduced tighter standards on a number of fuel properties affecting emissions. The principle changes in UK market petrol fuels were to the sulphur and benzene contents. The volatility of summer blends of petrol was also reduced, affecting evaporative emissions. The Directive states that the RVP during the summer period is limited to 60 kPa, with the summer period beginning no later than 1 May and not ending before 30 September. However, ‘for Member States with arctic conditions’, the summer period shall begin no later than 1 June and not end before 31 August and the RVP is limited to 70 kPa (Official Journal of the European communities, 1998). Being situated in northern Europe, the UK decided to conform with the 70 kPa option.

This change is also reflected in the British standards for unleaded petrol. For example, BS EN 228: 1999 states that the summer grade of unleaded petrol should be Class 4 (*i.e.* 45-80 kPa) and winter grade Class 8 (*i.e.* 70-100 kPa), whilst BS EN 228: 2000 states that the summer grade of unleaded petrol should be Class B (*i.e.* 45-70 kPa) and winter Class F (*i.e.* 70-100 kPa). This change amounts to a potential 10 kPa drop in vapour pressure between these standards, which came into force from 1 January 2000.

2.4.2 Vehicle technology

The first attempts to reduce evaporative emissions involved relatively simple mechanical modifications, such as pressurised fuel tanks with pressure/vacuum relief valves, sealing leaks, venting of the carburettor float-bowl into the air filter and venting of fuel tanks into the crankcase. In the United States, positive crankcase ventilation (PCV) was introduced in 1963. This aimed to recycle the blow-by vapours from the crankcase back into the intake manifold so that they could be re-burned. This virtually eliminated crankcase emissions as a source of air pollution. Sealed fuel systems and charcoal canisters appeared in 1971 (Hausberger *et al*., 2005).

Although there has been an increasing environmental concern with evaporative emissions, much more attention is usually paid to exhaust emissions. This has especially been the case in Europe, where contrary to the US, Japan and Australia, no evaporative emission limits were applied until 1993. Up to this point, numerous improvements in both evaporative control systems and testing standards were already introduced in the US. Consequently, the phase-in of vehicles with so-called ‘enhanced’ evaporative control systems started in the US in 1996 (Hausberger *et al*., 2005).

Most modern evaporative emission control systems employ an adsorption canister - filled with activated charcoal - which is connected to both the fuel tank and the engine intake manifold. Figure 1 shows a schematic diagram of a typical evaporative control system. Both the size and design of the canister have an effect on evaporative emissions.

The charcoal adsorbs any excess fuel vapour produced from the tank. The vapour can be then purged into the intake manifold when the engine is running under certain conditions, so that the VOCs can be burned along with the air-fuel mixture. On modern vehicles canister purge is controlled by a purge valve, which is placed between the charcoal canister and the engine intake manifold and is regulated by the engine management system (Hausberger *et al*., 2005).

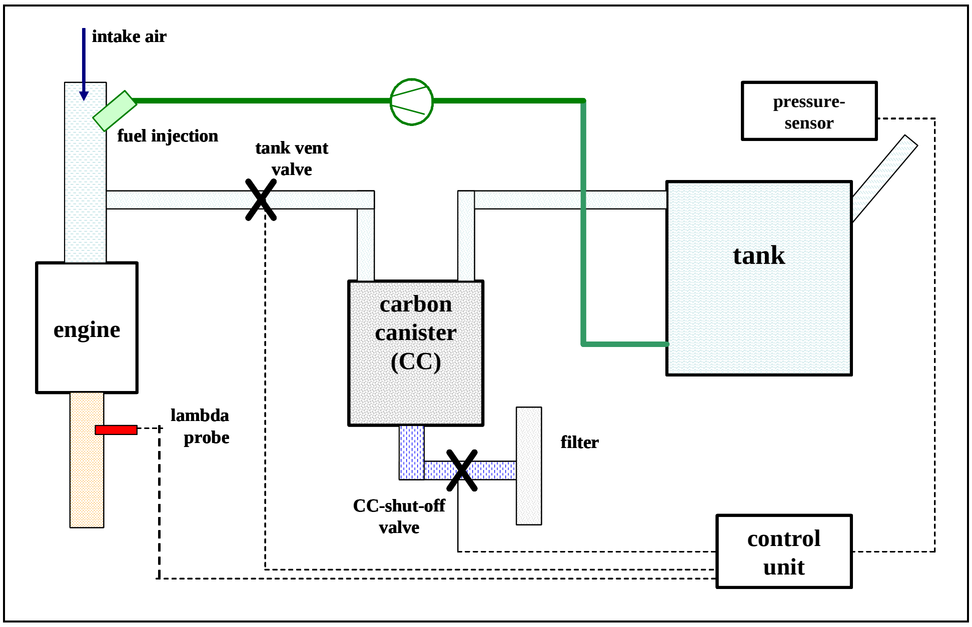

Figure 1: Basic components of an evaporative emission control system (Hausberger *et al*., 2005).

2.5 Measurement of evaporative emissions

Directive 98/69/EC describes a test method for the determination of VOCs emissions due to evaporation from the fuel systems of vehicles with spark-ignition engines. The test is designed to determine evaporative VOC emissions as a consequence of diurnal temperature fluctuations, hot soaks during parking, and urban driving. The test consists of three phases:

(i) Test preparation, including urban and extra-urban driving cycles.

(ii) Hot-soak emission determination.

(iii) Diurnal emission determination.

Mass emissions of VOCs from the hot-soak and the diurnal emission phases are added up to provide an overall result for the test.

The test procedure involves placing a vehicle inside a gas-tight measuring chamber equipped with sensors to monitor the temperature and VOC concentrations. The chamber is known as a SHED (Sealed Housing for Evaporative Determination). The atmosphere within the chamber is monitored using a hydrocarbon detector of the flame ionisation detector (FID) type. Hot-soak emissions are determined as the quantity of VOCs emitted during a period of one hour when the vehicle is cooling down after having undergone the driving cycles. ‘Cold soak’ emissions are determined from the quantity of HC emitted during the period when the temperature of the fuel tank is increased gradually. During the diurnal test the vehicle must be exposed to one cycle of ambient temperature.

3 The NAEI model

Details of the full NAEI methodology are available from the NETCEN web site[6], 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 specific method for estimating evaporative emissions is explained below, and some of its limitations are discussed.

3.1 Modelling approach

Evaporative emissions from the light-duty vehicle fleet are calculated on a monthly basis. The NAEI method takes into account three of the five mechanisms for evaporation described in Section 2.2:

- Diurnal emissions
- Hot-soak emissions
- Running emissions

Resting emissions not explicitly allowed for in the NAEI, and refuelling emissions are not considered as vehicle source.

For each of the three mechanisms included, equations relating evaporative emissions to ambient temperature and RVP were developed using the empirical formulae from a series of CONCAWE research studies in combination with UK measurements reported by TRL. Separate equations were developed for vehicles with and without evaporative control systems such as carbon canister devices. The overall methodology is similar to that given in COPERT II (Ahlvik *et al.*, 1997), but the data are considered by NETCEN to be more representative of the UK.

The NAEI uses equations for Euro 1 cars with ‘first-generation’ canister technology, based on early measurements, but for Euro 2-4 cars the equations are taken from COPERT III (Ntziachristos and Samaras, 2000). The COPERT equations lead to lower emissions, and better reflect the requirement for modern cars to meet the 2 grammes per test limit on evaporative emissions over the diurnal emission and hot-soak cycles under Directive 98/69/EC.

3.1.1 Diurnal emissions

For diurnal emissions, the equations for pre-Euro 1 (non-canister) and Euro 1 cars and LGVs[7] were developed from data and formulae reported by CONCAWE (1987), Barlow (1993) and ACEA (1995). Equations for Euro 2-4 cars were taken from COPERT III. The equations specified in Table 1 give diurnal emissions in g vehicle^{-1} day^{-1} for uncontrolled vehicles ($DL_{uncontrol.}$), and Euro 1 and Euro 2-4 canister-controlled vehicles ($DL_{Euro\ 1}$, $DL_{Euro\ 2\text{-}4}$). Total annual diurnal emissions are calculated using the equation:

$$E_{diurnal} = 365 \times N \times \left[(DL_{uncontrol.} \times F_{uncontrol.}) + (DL_{Euro\ 1} \times F_{Euro\ 1}) + (DL_{Euro\ 2\text{-}4} \times F_{Euro\ 2\text{-}4})\right]$$

(Equation 1)

where:

$E_{diurnal}$	=	Total diurnal emission (g year^{-1})
N	=	Number of petrol vehicles (cars and LGVs) in the UK fleet.
$DL_{uncontrol.}$	=	Diurnal loss emission rate for uncontrolled vehicles (g vehicle^{-1} day^{-1}).
$F_{uncontrol.}$	=	Fraction of vehicles not fitted with carbon canisters (assumed to be the same as the fraction of pre-Euro 1 vehicles).
$DL_{Euro\ 1}$, $DL_{Euro\ 2\text{-}4}$	=	Diurnal loss emission rates for canister-controlled vehicles (g vehicle^{-1} day^{-1}).
$F_{Euro\ 1}$	=	Fraction of Euro 1 vehicles in the fleet.
$F_{Euro\ 2\text{-}4}$	=	Fraction of Euro 2-4 vehicles in the fleet.

6 http://www.aeat.co.uk/netcen/airqual/naei/annreport/annrep99/app1_29.html

7 LGV = light goods vehicle.

This equation, given by Choudrie *et al*. (2008), clearly relates to annual emissions, and therefore appears to contradict the earlier statement that emissions are calculated monthly. It is assumed here that monthly values are actually used, and that the equation is adjusted accordingly.

3.1.2 Hot-soak emissions

For hot-soak emissions, the equations for cars and LGVs were developed from data and formulae reported by CONCAWE (1990), Barlow (1993) and COPERT II. The equations specified in Table 1 give hot-soak emissions in g vehicle^{-1} trip^{-1} for uncontrolled vehicles ($HS_{uncontrol.}$), and Euro 1 and Euro 2-4 canister-controlled vehicles ($HS_{Euro\ 1}$, $HS_{Euro\ 2\text{-}4}$). Total annual hot-soak emissions are calculated using the equation:

$$E_{hot\text{-}soak} = (VKM/l_{trip}) \times \left[(HS_{uncontrol.} \times F_{uncontrol.}) + (HS_{Euro\ 1} \times F_{Euro\ 1}) + (HS_{Euro\ 2\text{-}4} \times F_{Euro2\text{-}4})\right]$$

(Equation 2)

where:

$E_{hot\text{-}soak}$	=	Total hot-soak emission (g year^{-1})
VKM	=	Total number of vehicle kilometres driven in the UK by the petrol vehicles (cars and LGVs) (vehicle km year^{-1}).
l_{trip}	=	Average trip length (8.4 km in the UK).
$HS_{uncontrol.}$	=	Hot-soak emission factor for uncontrolled vehicles (g vehicle^{-1} trip^{-1}).
$F_{uncontrol.}$	=	Fraction of vehicles not fitted with carbon canisters (assumed to be the same as the fraction of pre-Euro 1 vehicles).
$HS_{Euro\ 1}$, $HS_{Euro\ 2\text{-}4}$	=	Hot-soak emission factor for canister-controlled vehicles (g vehicle^{-1} trip^{-1}).
$F_{Euro\ 1}$	=	Fraction of Euro 1 vehicles in the fleet.
$F_{Euro\ 2\text{-}4}$	=	Fraction of Euro 2-4 vehicles in the fleet.

Again, it is assumed here that the monthly values are calculated, rather than a single value for the year.

3.1.3 Running emissions

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

$$E_{running\ emission} = VKM \times \left[(RL_{uncontrol.} \times F_{uncontrol.}) + (RL_{controlled} \times F_{controlled})\right]$$

(Equation 3)

where:

$E_{running\ emission}$	=	Total running emissions (g year^{-1})
VKM	=	Total number of vehicle kilometres driven in the UK by the petrol vehicles (cars and LGVs) (vehicle km year^{-1}).
$RL_{uncontrol.}$	=	Running emission factor for uncontrolled vehicles (g vehicle^{-1} km^{-1}).
$F_{uncontrol.}$	=	Fraction of vehicles not fitted with carbon canisters (assumed to be the same as the fraction of pre-Euro 1 vehicles).
$RL_{Controlled.}$	=	Running emission factor for controlled vehicles (g vehicle^{-1} km^{-1}).
$F_{controlled}$	=	Total fraction of controlled vehicles in the fleet ($F_{Euro\ 1} + F_{Euro\ 2\text{-}4}$).

Table 1: Equations for diurnal, hot-soak and running emissions from cars and LGVs with and without control systems (Choudrie *et al*., 2008).

Vehicle type	Emission factor	Units	Equation
Uncontrolled vehicle (pre-Euro 1)	Diurnal emission ($DL_{uncontrolled}$)	g vehicle^{-1} day^{-1}	$1.54 * (0.51*T_{rise} + 0.62*T_{max} + 0.22*RVP - 24.89)$
	Hot-soak emission ($HS_{uncontrolled}$)	g vehicle^{-1} trip^{-1}	$\exp(-1.644 + 0.02*RVP + 0.0752*T_{mean})$
	Running emission ($RL_{uncontrolled}$)	g vehicle^{-1} km^{-1}	$0.022 * \exp(-5.967 + 0.04259*RVP + 0.1773*T_{mean})$
Carbon canister controlled vehicle (Euro 1)	Diurnal emission (DL_{EUI})	g vehicle^{-1} day^{-1}	$0.3 * DL_{uncontrolled}$
	Hot-soak emission (HS_{EUI})	g vehicle^{-1} trip^{-1}	$0.3 * \exp(-2.41 + 0.02302*RVP + 0.09408*T_{mean})$
	Running emission ($RL_{controlled}$)	g vehicle^{-1} km^{-1}	$0.1 * RL_{uncontrolled}$
Carbon canister controlled vehicle (Euro 2-4)	Diurnal emission ($DL_{EUII-IV}$)	g vehicle^{-1} day^{-1}	$0.2 * 9.1 * \exp(0.0158*(RVP-61.2) + 0.0574*(T_{max}-T_{rise}-22.5) + 0.0614*(T_{rise}-11.7))$
	Hot-soak emission ($HS_{EUII-IV}$)	g vehicle^{-1} trip^{-1}	0
	Running emission ($RL_{controlled}$)	g vehicle^{-1} km^{-1}	$0.1 * RL_{uncontrolled}$

T_{rise} = diurnal rise in temperature in ^oC
T_{max} = maximum daily temperature in ^oC
T_{mean} = annual mean temperature in ^oC (it is assumed here that this should read 'monthly mean')
RVP = Reid vapour pressure of petrol in kPa

3.2 Temperature and RVP data

Temperature data for Central England (supplied by the Met Office) are used in the NAEI. The monthly average RVP of petrol sold in the UK is based on historic trends and information from UKPIA[8] relating to summer and winter blends of fuels in recent years, and their turnover patterns at filling stations. The average RVPs of summer and winter petrol are 68 kPa and 92 kPa respectively (Choudrie *et al*., 2008)

3.3 Deficiencies in the NAEI model

The NAEI approach for evaporative emissions is based largely on the COPERT II and COPERT III models, combined with supporting experimental data from before 1995. However, the supporting data sets are small and outdated, and do not account for the significant improvements in the control of evaporative emission which began with the introduction of Euro 3 vehicles, enhanced evaporative systems and on-board diagnostics. Another important deficiency in the NAEI method is that it is based on tests on vehicles which were less than three years old when they were measured. Therefore, the NAEI does not account for a potential increase in evaporative emissions with vehicle age, especially for vehicles with malfunctioning evaporation-control systems. As some USEPA studies have shown, a fraction of vehicles in the in-use fleet do not function as designed, and generate substantially elevated emissions (*e.g.* Landman, 2001). Consequently, a few vehicles can account for a large proportion of the in-use emissions.

[8] UKPIA = UK Petroleum Industry Association.

4 The ARTEMIS model

4.1 The measurement programme

The ARTEMIS model for evaporative emissions updated previous European estimation approaches, and provided a greater level of detail for a wider range of vehicle categories.

In the ARTEMIS programme, tests were performed on typical European cars at a number of laboratories (Hausberger *et al.*, 2005). The test programme was designed so that evaporative diurnal emissions could be measured over different temperature cycles (*i.e.* different minimum diurnal temperatures and diurnal temperature variations), and over European and US test procedures. Three Euro 3 cars (rated power of 70, 90 and 140 kW) and a motorcycle (rated at 78 kW) were used for the tests. The RVP of the test fuel (58.3 kPa) was more typical of a general European fuel rather than UK summer petrol (68 kPa). Whilst the use of this fuel meant that the tests did not exactly replicate the UK situation, the subsequent equations derived for the ARTEMIS model do allow for changes in fuel volatility between summer and winter petrol blends.

One of the objectives of the ARTEMIS programme was to determine the suitability of the USEPA's MOBILE 6 model (which is based on comprehensive test data) for predicting evaporative emissions from European vehicles. Since the ARTEMIS tests yielded results for Euro 3/4 vehicles which were similar to those obtained by the EPA for 'enhanced' US cars, the use of US data was not considered to be problematic (Hausberger *et al.*, 2005).

The ARTEMIS evaporative emission factors are based on the MOBILE 6 and the COPERT models, adapted to take into account the results of the ARTEMIS measurement programme. Methods for estimating evaporative emissions from motorcycles and mopeds are also included. The ARTEMIS approach is discussed in the following Sections.

4.2 Real-time diurnal emissions

In ARTEMIS real-time diurnal (RTD) emissions are defined as a separate category. RTD emissions are a combination of diurnal and resting emissions

4.2.1 Diurnal Emissions

For diurnal emissions, formulae from MOBILE 6 (adjusted to SI units) are used. The vapour pressure (VP) of the fuel is calculated as a function of the RVP and temperature. A vapour pressure product term (***VP**$_{mean}$•**ΔVP***) is then determined. This is the product of average vapour pressure during the temperature cycle and the vapour pressure difference over the cycle.

The vapour pressure (VP) can be calculated according to Clausius-Clapeyron equation from the RVP:

$$VP = RVP \times e^{A \times \left(\frac{1}{T_{abs}} - \frac{1}{310.9}\right)} \text{ (kPa)} \qquad \text{(Equation 4)}$$

where:

$$A = -3565.2707 + 10.23 \times RVP$$

If VP_{mean} is the average vapour pressure over the temperature cycle:

$$VP_{mean} = \frac{VP_{T\max} + VP_{T\min}}{2} \text{ (kPa)} \qquad \text{(Equation 5)}$$

ΔVP (difference between VP at highest and lowest ambient temperature in the cycle) is:

$$\Delta VP = VP_{T\,\max} - VP_{T\,\min} \quad \text{(kPa)} \qquad \text{(Equation 6)}$$

$(VP_{mean} \times \Delta VP)$ is called the VP product term according to the nomenclature in MOBILE 6.

Passenger cars

For pre-Euro 1 and 'Euro 1-4 failure' vehicles, the parameters from MOBILE 6 for the model year range 1986-1995 with 'fail pressure' were used for the ARTEMIS model[9] (Equation 7). For Euro 1 and 2 vehicles, the model year range 1986-1995 with 'pass both' was used. The parameters ***A*** and ***B*** for Euro 3 and 4 vehicles were adapted according to the ARTEMIS measurement results (Table 2), since the MOBILE 6 formula for enhanced vehicles is not based on tests but is simply assumed to reduce emissions by 50% compared with the previous models. The measurements performed in ARTEMIS showed lower emission levels for these cars.

$$e_{Diurnal} = A + B \times \frac{(VP_{mean} \times \Delta VP)^2}{1000} \quad \text{(g day}^{-1}\text{)} \qquad \text{(Equation 7)}$$

Table 2: Parameters for calculating diurnal emissions from cars.

Vehicle category	***A***	***B***
Pre-Euro 1 and 'Euro 1-4 failure'	0.478	0.015
Euro 1 and Euro 2	0.388	0.005
Euro 3 and Euro 4	0.037	0.00136

Motorcycles and mopeds

The diurnal and resting emissions for motorcycles and mopeds are calculated according to the methodology suggested for pre-Euro 1 passenger cars (since these do not have evaporative emission-control systems), but are adjusted in accordance with the fuel tank volume.

Diurnal emissions for motorcycles (>50 cc):

$$e_{Diurnal} = 0.5 \times e_{Diurnal,\ passenger\ car\ pre-Euro1} \quad \text{(g day}^{-1}\text{)} \qquad \text{(Equation 8)}$$

Diurnal emissions for mopeds (<50 cc):

$$e_{Diurnal} = 0.2 \times e_{diurnal,\ passenger\ car\ pre-Euro1} \quad \text{(g day}^{-1}\text{)} \qquad \text{(Equation 9)}$$

4.2.2 Resting emissions

Resting emissions for cars are calculated using the following equation, and using the coefficients in Table 3. The allocation between vehicle categories in MOBILE 6 and ARTEMIS is similar to that for the allocation of diurnal emissions.

$$e_{resting} = K \times \left[A + 0.0051 \times t_{\min}\right] \times 24 \quad \text{(if results are below zero, } e_{Resting} = 0\text{)} \qquad \text{(Equation 10)}$$

[9] The limited number of European vehicles tested did not allow many different vehicle categories to be accurately defined. Thus, several vehicle categories from MOBILE 6 were merged for the ARTEMIS approach.

Table 3: Parameters for calculating resting emissions from cars.

Vehicle category	*K*	*A*
Pre-Euro 1 and ‘Euro 1-4 failure’	1	-0.019
Euro 1 and Euro 2	1	-0.051
Euro 3 and Euro 4	0.25	-0.051

The resting emissions for motorcycles (>50 cc) and mopeds (<50cc) are also based on cars and adjusted in the same way as for diurnal emissions.

$$e_{resting} = 0.5 \times e_{resting,\ passenger\ car\ pre-Euro\ 1} \quad (\text{g day}^{-1}) \qquad \text{(Equation 11)}$$

$$e_{resting} = 0.2 \times e_{resting,\ passenger\ car\ pre-Euro\ 1} \quad (\text{g day}^{-1}) \qquad \text{(Equation 12)}$$

4.3 Hot-soak emissions

The MOBILE 6 equations are taken as the basis for the suggested formulae, since they are also based on a large database for older vehicles with failures in their evaporative emission-control systems.

4.3.1 Pre-Euro 1 and ‘Euro 1-4 with failure’ vehicles

For pre-Euro 1 and ‘Euro 1-4 with failure’ vehicles, the MOBILE 6 formula for cars with fuel injection and ‘fail pressure’ is used. A separate equation for pre-Euro 1 cars with a carburettor is not used due to the small differences in the emission level and the high uncertainty in the relative proportions of pre-Euro 1 vehicles with a carburettor or fuel injection in the fleet. The parameters ***A***, ***B***, and ***C*** were adapted from MOBILE 6 to be compatible with SI units (see Table 4).

$$e_{HS\ Pre-Euro1\ /\ Euro\ 1-4\ Failure} = 0.88 \times e^{[A \times (RVP - 62) + B \times t_a + C]} \quad (\text{g test}^{-1}) \qquad \text{(Equation 13)}$$

Table 4: Parameters for hot-soak emissions from pre-Euro 1 vehicles and Euro 1-4 vehicles with failures.

Vehicle category	*A*	*B*	*C*
Pre-Euro 1 and ‘Euro 1-4 failure’	0.06	0.0926	-0.8

4.3.2 Euro 1 and 2 cars

For ‘Euro 1 and 2’ vehicles, the MOBILE 6 formula for cars with port fuel injection and without failure is used. The parameters ***A***, ***B***, and ***C*** were again adapted from MOBILE 6 to be compatible with SI units (Table 5).

$$e_{HS\ E1+2} = \frac{(A + B \times RVP) \times (t_a + C)}{D} \quad (\text{g test}^{-1}) \qquad \text{(Equation 14)}$$

Table 5: Parameters for hot-soak emissions of Euro 1 and Euro 2 cars.

Vehicle category	***A***	***B***	***C***	***D***
Euro 1-4	-0.098	0.12	17.8	740

4.3.3 Euro 3 and 4 cars

According to the ARTEMIS test results, the enhanced controlled cars had approximately 75% lower hot-soak emissions than the EPA model for enhanced cars (*i.e.* Euro 1 and Euro 2 cars).

$$e_{HS\ E\,3+4} = 0.25 \times e_{HS\ E\,1+2} \qquad \text{(Equation 15)}$$

Since a hot-soak test represents the evaporative emissions during a cool down from a fully warmed-up vehicle, this is assumed to be equivalent to 'grammes per trip' in the NAEI.

4.3.4 Motorcycles (>50cc)

Constant values are used in ARTEMIS for hot-soak emissions from motorcycles (Hausberger *et al*., 2005). The values, which relate to urban and rural/motorway driving, are given in Table 6. The value for urban driving was derived from tests over the New European Driving Cycle (NEDC), and the value for rural and motorway from tests over the World Motorcycle Test Cycle (WMTC). It is assumed that outside cities the average driver uses an engine load in the range of the WMTC (or higher). This results in quite high engine temperatures after shut-off, and correspondingly large increases in the temperature of the fuel tank, which is usually located above the engine. Due to the higher engine temperature after shut-off, the hot-soak emissions are approximately 2.6 times higher after the WMTC than after the NEDC, hence the difference in the evaporative emission factors for motorcycles in Table 6.

Table 6: Hot-soak emissions motorcycles>50 cc (g test^{-1}).

Vehicle category	Urban	Rural & motorway
e_{HS} > 50cc	2.5	6.4

4.3.5 Mopeds (<50cc)

As for motorcycles, a constant value is used for mopeds in ARTEMIS. Since engine loads should be similar during urban and rural driving, one constant factor is used:

$$e_{HS\ M<50cc} = 0.6 \quad (\text{g test}^{-1}) \qquad \text{(Equation 16)}$$

4.4 Running emissions

4.4.1 Cars

For running emissions, the equations from COPERT III were used as a basis for the ARTEMIS model. Since urban evaporative emissions are much higher (in terms of g km^{-1}) than rural or motorway emissions, additional parameters ***A***, ***B***, and ***C*** are introduced into the formula[10] according to the road category (Hausberger *et al*., 2005). These parameters were derived from the results of USEPA studies in which the running emissions are

[10] Basing the running emissions on g h^{-1} does not eliminate the differences between cycles, and therefore units of g km^{-1} were used.

given for three different cycles of 11.5 km h^{-1}, 31.5 km h^{-1} and 77 km h^{-1}. The parameters ***A***, ***B***, and ***C*** were calculated from these experimental data by multiple regression analysis, and are listed in Table 7.

$$e_{Running} = A \times 0.136 \times e^{(-5.967 + B \times 0.04259 \times RVP + C \times 0.1773 \times t_a)} \quad (\text{g km}^{-1}) \qquad \text{(Equation 17)}$$

Table 7: Parameters for running emissions.

Vehicle category and road type		*A*	*B*	*C*
Pre Euro/ Euro 1-4 failure	Urban	11	1.2	0.72
	Rural	10	0.98	0.67
	Motorway	4.5	0.95	0.67
Euro 1-4	Urban	1	1.1	0.79
	Rural	0.5	0.95	0.71
	Motorway	0.1	0.8	0.67

4.4.2 Motorcycles and Mopeds

No measurements on running emissions from mopeds and motorcycles were identified during the ARTEMIS project.

4.5 Failure of evaporative emissions systems

The proportion of Euro 1 to Euro 4 cars with failures in the control system in ARTEMIS (R_{FV}) is calculated according to the results of the USEPA 'fail pressure' data from in-use tests in the United States. The rate of failure is assumed to be lower for Euro 3 and 4 due to the introduction of on-board diagnostics and the durability requirements of the emission-control systems. No data exist which permit the assessment of the situation in Europe. However, it is assumed that it is preferable to use the US data on failures rather than to assume that European cars do not have any failures at all in their fuel systems.

Euro 1 and 2: $$R_{FV\ EURO\ I\ and\ II} = \frac{0.6045}{1 + 17.333 \times e^{\left[-0.01362 \times (Age)^2\right]}} \qquad \text{(Equation 18)}$$

Euro 3 and 4: $$R_{FV\ EURO\ III\ and\ IV} = \frac{0.6045}{1 + 17.333 \times e^{\left[-0.01362 \times \left(\frac{Age}{2}\right)^2\right]}} \qquad \text{(Equation 19)}$$

Where the ***Age*** is stated in years, and $0 \le R_{FV} \le 1$.

5 The COPERT 4 model

In December 2008, a draft revision to the 'Gasoline Evaporation from Vehicles' Chapter of the EMEP/CORINAIR Emission Inventory Guidebook was produced[11]. It was also proposed that this method would also be used in COPERT 4. Three methods are provided – 'Tier 1', 'Tier 2' and 'Tier 3'. The Tier 1 method is rather simplistic (being based on highly aggregated emission factors) and is not described here. The Tier 2 and Tier 3 methods are described below, and are referred to as 'COPERT 4' in this Report.

5.1 Tier 2 method

The main equation used for estimating evaporative emissions is:

$$E_{eva,voc,j} = 365 \times N_j \times (HS_j + e_{d,j} + RL_j) \qquad \text{(Equation 20)}$$

where:

$E_{eva,voc,j}$ = Annual VOC emissions due to evaporative losses of vehicles in category j (g).
N_j = Number of petrol vehicles of category j.
HS_j = Average daily hot and warm soak emissions of vehicle category j (g day^{-1}).
$e_{d,j}$ = Average diurnal losses of vehicle category j (g day^{-1}).
RL_j = Average daily hot and warm running losses of vehicle category j (g day^{-1}).

and

$$HS_j = x\,\{c\,[p\,e_{s,hot,c} + (1-p)\,e_{s,warm,c}] + (1-c)\,e_{s,hot,fi}\} \qquad \text{(Equation 21)}$$

$$RL_j = x\,\{c\,[p\,e_{r,hot,c} + (1-p)\,e_{r,warm,c}] + (1-c)\,e_{r,hot,fi}\} \qquad \text{(Equation 22)}$$

where:

x = Mean number of trips per vehicle per day, averaged over the year (trips per day).
c = Fraction of petrol-engined vehicles with a carburettor and/or fuel return system.
p = Fraction of trips finished with hot engine and catalyst (dependent on the average monthly ambient temperature).
$e_{s,hot,c}$ = Hot-soak emission factor of petrol vehicles with carburettor and/or fuel return system (dependent on fuel volatility and average monthly temperature) (g per procedure).
$e_{s,warm,c}$ = Cold- and warm-soak emission factor of petrol vehicles with carburettor and/or fuel return system (dependent on fuel volatility and average monthly temperature) (g per procedure).
$e_{s,hot,fi}$ = Hot-soak emission factor of petrol vehicles with fuel injection and 'returnless' fuel system (dependent on fuel volatility and average monthly temperature) (g per procedure).
$e_{r,hot,c}$ = Emission factor for hot running losses of petrol vehicles with carburettor and/or fuel return systems (dependent on fuel volatility and average monthly ambient temperature) (g trip^{-1}).
$e_{r,warm,c}$ = Emission factor for cold and warm running losses of petrol vehicles with carburettor and/or fuel return system (dependent on fuel volatility and average monthly temperature) (g trip^{-1}).
$e_{r,hot,fi}$ = Emission factor for hot running losses of petrol vehicles with fuel injection and returnless fuel system (dependent on fuel volatility and average monthly temperature) (g trip^{-1}).

The number of trips per day, if not known from statistical data, can be estimated using the expression:

$$x = M_j / (365 \times l_{trip}) \qquad \text{(Equation 23)}$$

where M_j is the total annual mileage of petrol vehicles of category j.

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

The fraction of trips finished with a cold or warm engine (1-$\boldsymbol{p}$) is linked to a parameter $\boldsymbol{\beta}$, which is also used in the calculation of cold-start emissions: both depend, amongst other things, on ambient temperature. In the absence of better data, it is assumed that (1-$\boldsymbol{p}$) ≈ $\boldsymbol{\beta}$. The $\boldsymbol{\beta}$ parameter also depends on the average trip length $\boldsymbol{l_{trip}}$. This indicates that, for the calculation of cold-start emissions and soak emissions, the average trip length is of great importance. In order to apply Equation (20), Table 8 provides basic emission factors for petrol cars in three different size classes, and Table 9 for two-wheel vehicles. Emission factors are given for typical temperature ranges in winter and summer, and typical fuel vapour pressures. For canister-equipped passenger cars, three different carbon canister sizes (small, medium, large) were considered, depending on vehicle engine size and technology as indicated in Table 13.

Table 8: Evaporative emission factors for petrol passenger cars under typical summer and winter conditions.

Season	Summer		Winter		Summer		Winter		Summer		Winter	
Temperature variation (^{o}C)	20-35	10-25	0-15	-5-10	20-35	10-25	0-15	-5-10	20-35	10-25	0-15	-5-10
Fuel DVPE (kPa)[12]	60	70	90	90	60	70	90	90	60	70	90	90
	<1.4 l - uncontrolled				1.4-2.0 l - uncontrolled				>2.0 l - uncontrolled			
e_d (g/day)	3.90	2.35	1.74	1.24	4.58	2.76	2.04	1.45	5.59	3.36	2.49	1.77
$e_{s,hot,fi}$ (g/procedure)	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04
$e_{s,warm,c}$ (g/procedure)	8.48	5.09	3.75	2.63	10.01	6.01	4.42	3.10	12.29	7.38	5.43	3.80
$e_{s,hot,c}$ (g/procedure)	11.93	7.16	5.27	3.69	14.08	8.45	6.22	4.36	17.31	10.39	7.65	5.35
$e_{r,hot,fi}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,warm,c}$ (g/trip)	1.84	1.11	0.81	0.53	2.15	1.30	0.95	0.67	2.62	1.58	1.15	0.81
$e_{r,hot,c}$ (g/trip)	10.05	6.03	4.44	3.11	11.85	7.12	5.24	3.67	14.56	8.74	6.43	4.50
	<1.4 l - small canister				1.4-2.0 l - small canister				>2.0 l - small canister			
e_d (g/day)	0.61	0.15	0.11	0.10	0.95	0.17	0.11	0.10	1.57	0.21	0.11	0.10
$e_{s,hot,fi}$ (g/procedure)	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04
$e_{s,warm,c}$ (g/procedure)	0.63	0.13	0.06	0.04	0.96	0.15	0.06	0.04	1.82	0.20	0.06	0.04
$e_{s,hot,c}$ (g/procedure)	1.74	0.20	0.06	0.04	2.87	0.26	0.07	0.05	4.92	0.43	0.09	0.05
$e_{r,hot,fi}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,warm,c}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,hot,c}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
	<1.4 l - medium canister				1.4-2.0 l - medium canister				>2.0 l - medium canister			
e_d (g/day)	0.24	0.13	0.10	0.10	0.26	0.13	0.10	0.10	0.32	0.14	0.10	0.10
$e_{s,hot,fi}$ (g/procedure)	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04
$e_{s,warm,c}$ (g/procedure)	0.22	0.09	0.05	0.04	0.26	0.09	0.05	0.04	0.35	0.10	0.05	0.04
$e_{s,hot,c}$ (g/procedure)	0.35	0.10	0.05	0.04	0.45	0.11	0.05	0.04	0.70	0.13	0.06	0.04
$e_{r,hot,fi}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,warm,c}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,hot,c}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
	<1.4 l - large canister				1.4-2.0 l - large canister				>2.0 l - large canister			
e_d (g/day)	0.20	0.13	0.10	0.10	0.20	0.13	0.10	0.10	0.21	0.13	0.10	0.10
$e_{s,hot,fi}$ (g/procedure)	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04	0.10	0.07	0.04	0.04
$e_{s,warm,c}$ (g/procedure)	0.15	0.07	0.05	0.04	0.16	0.08	0.05	0.04	0.17	0.08	0.05	0.04
$e_{s,hot,c}$ (g/procedure)	0.18	0.08	0.05	0.04	0.20	0.08	0.05	0.04	0.23	0.09	0.05	0.04
$e_{r,hot,fi}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,warm,c}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04
$e_{r,hot,c}$ (g/trip)	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04	0.13	0.08	0.06	0.04

[12] DVPE = dry vapour pressure equivalent.

Table 9: Evaporative emission factors for two-wheel vehicles under typical summer and winter conditions.

Season	Summer		Winter		Summer		Winter		Summer		Winter	
Temperature variation (°C)	20-35	10-25	0-15	-5-10	20-35	10-25	0-15	-5-10	20-35	10-25	0-15	-5-10
Fuel DVPE (kPa)	60	70	90	90	60	70	90	90	60	70	90	90
	Mopeds <50 cm³				Motorcycles 2-stroke >50 cm³				Motorcycles 4-stroke <250 cm³			
e_d (g/day)	0.59	0.37	0.28	0.22	0.79	0.49	0.37	0.28	0.93	0.57	0.43	0.33
$e_{s,hot,fi}$ (g/procedure)	0.27	0.16	0.12	0.08	0.41	0.25	0.18	0.13	0.50	0.30	0.22	0.15
$e_{s,hot,c}$ (g/procedure)	0.69	0.41	0.30	0.21	1.03	0.62	0.45	0.32	1.26	0.75	0.55	0.39
$e_{r,hot,fi}$ (g/trip)	0.19	0.11	0.08	0.06	0.28	0.17	0.12	0.09	0.34	0.21	0.15	0.11
$e_{r,hot,c}$ (g/trip)	0.49	0.30	0.22	0.15	0.74	0.44	0.33	0.23	0.90	0.54	0.40	0.28
	Motorcycles 4-stroke 250-750 cm³				Motorcycles 4-stroke >750 cm³ uncontrolled				Motorcycles 4-stroke >750 cm³ small			
e_d (g/day)	1.47	0.89	0.67	0.49	1.60	0.97	0.73	0.53	0.22	0.13	0.10	0.10
$e_{s,hot,fi}$ (g/procedure)	0.86	0.52	0.38	0.27	0.95	0.57	0.42	0.29	0.02	0.00	0.00	0.00
$e_{s,hot,c}$ (g/procedure)	2.17	1.30	0.96	0.67	2.40	1.44	1.06	0.74	0.05	0.01	0.00	0.00
$e_{r,hot,fi}$ (g/trip)	0.59	0.35	0.26	0.18	0.65	0.39	0.29	0.20	0.01	0.00	0.00	0.00
$e_{r,hot,c}$ (g/trip)	1.56	0.94	0.69	0.48	1.73	1.03	0.76	0.53	0.03	0.01	0.00	0.00

The fraction of vehicles equipped with a carburettor and/or fuel return systems is required in order to apply Equations 21 and 22. In Europe, the fraction of passenger cars and LDVs equipped with a carburettor is approximately 99% for pre-Euro 1 vehicles (*i.e.* only 1% equipped with fuel injection) and 0% for post-Euro 1 vehicles. For motorcycles this fraction is 100% for conventional and Euro 1 vehicles, 20% for Euro 2 and 0% for Euro 3. These figures could be used where there is a lack of detailed national statistical data.

5.2 Tier 3 method

Equation (20) can be also used to estimate evaporation emissions with the detailed 'Tier 3' methodology. The proposed methodology has been based on results from a range of canister-equipped petrol vehicles which were representative of Euro 3/4 technology, and typical summer and winter fuels and temperatures. Although a large number of hot-soak and diurnal tests have been carried out, running losses were not measured and therefore the proposed emission factors need further improvement. Other areas requiring additional consideration include:

- Evaporative emission factors for light duty vehicles.
- Evaporative emission factors for fuels containing bio components (*e.g.* ethanol).

The Tier 3 method is based on a number of input parameters, which include (i) fuel vapour pressure, (ii) vehicle tank size, (iii) fuel tank fill level, (iv) canister size, (v) diurnal temperature variation and (vi) cumulative mileage. Since a parking event may occur anytime during the day a daily parking pattern is suggested, and a function is provided for estimating the temperature variation during the parking event. Based on these, intermediate calculations for the estimation of fuel vapour generation and the canister weight are performed for each parking event. Then, breakthrough emissions (for canister-equipped vehicles) or tank emissions (for carburetted vehicles) are calculated, as well as emissions due to fuel permeation and/or leakage. The total evaporative emissions for each evaporation process (diurnal emissions, hot-soak emissions and running losses) are determined by the sum of breakthrough or tank emissions and emissions due to fuel permeation and/or leakage.

5.2.1 Diurnal temperature variation

Diurnal losses take place during vehicle parking, as the ambient temperature varies during the day. To calculate diurnal losses both the temperature variation and the parking distribution during the day need to be known. The diurnal temperature variation may be simulated using a probability density function of a normal distribution between the minimum and the maximum ambient temperatures given by the following equation:

$$T = T_{\min} + T_{rise}\, e^{-0.0247(t-14)^2} \quad \text{(Equation 24)}$$

Where

t	=	Hour of the day (h)
T_{min}	=	Minimum daily temperature (°C)
T_{max}	=	Maximum daily temperature (°C)
T_{rise}	=	Rise in the daily temperature, calculated as $T_{max} - T_{min}$ (°C)

The minimum and maximum temperatures need to be calculated over a complete parking period. A parking period can be defined from the end-time of the parking period and the parking duration t_{park}. In order to estimate diurnal losses in detail, the parking duration can be distributed into 24 time classes ranging from <0.5 hours to >11.5 hours.

Each combination of parking duration and parking end-time has a probability factor f_k as shown in Table 10. The sum of f_k values in Table 10 equals 1.

Table 10: Parking time distribution (f_k values) as a function of parking end-time.

Parking end time t_2 (hh:mm)	Parking duration t_{park} (h)				
	<0.5	1	1.5	…	>11.5
01:00	f_1	f_2	f_3	…	f_{24}
02:00	f_{25}	f_{26}	f_{27}	…	f_{48}
03:00	f_{49}	f_{50}	f_{49}	…	F_{72}
…	…	…	…	…	…
24:00	f_{553}	f_{554}	f_{555}	…	f_{576}

The start time of parking may be calculated as $t_1 = t_2 - t_{park}$.

5.2.2 Fuel tank vapour generation

The vapour generation in the fuel tank (g) may be calculated as a function of fuel volatility, temperature variation, fuel tank size and fill level using the following equation (Reddy, 1989):

$$m_{tank}(T_{1,k}, T_{2,k}) = (1-h/100)\, v_{tank}\, (0.0205\, e^{0.0205vp}\, (e^{0.0716\, T2,k} - e^{0.0716\, T1,k})) \quad \text{(Equation 25)}$$

where:

h	=	Fuel tank fill level (%)
v_{tank}	=	Fuel tank, fuel system and vapour control system volume (l)
vp	=	Fuel vapour pressure (DVPE) (kPa)
$T_{1,k}$	=	Minimum tank temperature during parking period k (°C)
$T_{2,k}$	=	Maximum tank temperature during parking period k (°C)

The above equation is valid only for the fraction of the parking period for which the temperature increases. For a continuous temperature decrease (*e.g.* after the daily maximum value) there is no vapour generated in the fuel tank ($m_{tank} = 0$).

5.2.3 Canister breakthrough emissions

Based on experimental work on carbon canisters (Mellios and Samaras, 2007), the canister weight gain during loading with fuel vapour is described by the following equations:

$$m_{ads} = m_{load} - e^{(a + b \times s \times m_{load})} \qquad \text{(Equation 26)}$$

and

$$a = -11 - 0.015vp + 0.065T \qquad \text{(Equation 27)}$$

$$b = 0.115 - 0.00015vp + 0.0001T \qquad \text{(Equation 28)}$$

where:

m_{ads} = Cumulative fuel vapour adsorbed on the carbon canister during loading (g)
m_{load} = Cumulative fuel vapour loaded to the carbon canister (g)
s = Canister size (s = 2 for small, s = 1 for medium and s = 0.5 for large)

The initial canister weight is determined from the cumulative mileage of the vehicle as:

$$m_{ads,1} = 1/s\ [8.13 \ln(M_{cum,j}) - 22.92] \qquad \text{(Equation 29)}$$

where $M_{cum,j}$ is the cumulative mileage of vehicle category j.

The initial amount of vapour loaded on the canister $m_{load,1}$ is calculated by Equations (26)-(28) for the vapour pressure and the initial temperature of the fuel in the tank. This vapour load corresponds to the amount of vapour needed to increase the canister weight from 'dry' to its initial weight at the beginning of the parking period. The amount of fuel vapour generated over the parking period is calculated by Equation (25), and it is then added to $m_{load,1}$ to give the final vapour load $m_{load,2}$. The canister breakthrough emissions (g) are then calculated as:

$$m_{break}(T_{1,k},T_{2,k}) = e^{(a+b\times s\times m_{load,2})} - e^{(a+b\times s\times m_{load,2})} \qquad \text{(Equation 30)}$$

5.2.4 Permeation and leakage emissions

The mean emission factor (g h^{-1}) is given by the following equation:

$$m_{perm}(T) = e^{0.004\cdot vp} \times (6.1656\times10^{-6}\ T^{2.5} + 0.0206) \qquad \text{(Equation 31)}$$

The permeation emissions (g) over a parking period k are thus calculated as:

$$m_{perm}(T_{1,k},T_{2,k}) = \sum_{T_{1,k}}^{T_{2,k}} e^{0.004\cdot vp}(6.1656\times10^{-6}T^{2.5} + 0.0206) \qquad \text{(Equation 32)}$$

5.2.5 Activity statistics

The methodology requires a number of statistics which are unlikely to be available in many countries (*e.g.* the parameters p, c, x, t_{park}, t_{trip} and l_{trip}. These data can be found in detailed national statistics or various experimental studies (*e.g.* André *et al.*, 1994). Values for the UK are shown in Table 11 below. Table 12 gives suggested input data for the parking time distribution, and Tables 13 and 14 give vehicle design characteristics for cars/LDVs and mopeds/motorcycles respectively.

Table 11: Average statistics for the UK.

Average daily use of vehicles		Average trip characteristics	
Number of trips/day	4.7	Average length (km)	8.4
Driving duration (min)	58	Average duration (min)	12.1
Daily distance (km)	41.0	Average speed (km h^{-1})	41.5

Table 12: Parking time distribution.

Parking end-time t_2 (hh:mm)	Parking duration t_{park} (h) 0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	
0:00	0.94%	0.31%	0.04%	0.11%	0.13%	0.04%	0.07%	0.03%	0.03%	0.02%	0.02%	0.01%	0.02%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.30%	2.2%
1:00	0.51%	0.17%	0.02%	0.06%	0.07%	0.02%	0.04%	0.02%	0.02%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.17%	1.2%
2:00	0.30%	0.10%	0.01%	0.04%	0.04%	0.01%	0.02%	0.01%	0.01%	0.01%	0.01%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.10%	0.7%
3:00	0.17%	0.06%	0.01%	0.02%	0.02%	0.01%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.06%	0.4%
4:00	0.30%	0.10%	0.01%	0.04%	0.04%	0.01%	0.02%	0.01%	0.01%	0.01%	0.01%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.10%	0.7%
5:00	0.94%	0.31%	0.04%	0.11%	0.13%	0.04%	0.07%	0.03%	0.03%	0.02%	0.02%	0.01%	0.02%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.30%	2.2%
6:00	1.97%	0.64%	0.09%	0.23%	0.28%	0.09%	0.14%	0.07%	0.07%	0.05%	0.05%	0.02%	0.05%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.63%	4.6%
7:00	2.40%	0.78%	0.11%	0.28%	0.34%	0.11%	0.17%	0.08%	0.08%	0.06%	0.06%	0.03%	0.06%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.77%	5.6%
8:00	2.23%	0.72%	0.10%	0.26%	0.31%	0.10%	0.16%	0.08%	0.08%	0.05%	0.05%	0.03%	0.05%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.72%	5.2%
9:00	2.23%	0.72%	0.10%	0.26%	0.31%	0.10%	0.16%	0.08%	0.08%	0.05%	0.05%	0.03%	0.05%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.72%	5.2%
10:00	2.27%	0.74%	0.11%	0.27%	0.32%	0.11%	0.16%	0.08%	0.08%	0.05%	0.05%	0.03%	0.05%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.73%	5.3%
11:00	2.35%	0.76%	0.11%	0.28%	0.33%	0.11%	0.17%	0.08%	0.08%	0.06%	0.06%	0.03%	0.06%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.76%	5.5%
12:00	1.97%	0.64%	0.09%	0.23%	0.28%	0.09%	0.14%	0.07%	0.07%	0.05%	0.05%	0.02%	0.05%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.63%	4.6%
13:00	2.23%	0.72%	0.10%	0.26%	0.31%	0.10%	0.16%	0.08%	0.08%	0.05%	0.05%	0.03%	0.05%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.72%	5.2%
14:00	2.40%	0.78%	0.11%	0.28%	0.34%	0.11%	0.17%	0.08%	0.08%	0.06%	0.06%	0.03%	0.06%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.77%	5.6%
15:00	2.48%	0.81%	0.12%	0.29%	0.35%	0.12%	0.17%	0.09%	0.09%	0.06%	0.06%	0.03%	0.06%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.80%	5.8%
16:00	2.78%	0.90%	0.13%	0.33%	0.39%	0.13%	0.20%	0.10%	0.10%	0.07%	0.07%	0.03%	0.07%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.90%	6.5%
17:00	2.78%	0.90%	0.13%	0.33%	0.39%	0.13%	0.20%	0.10%	0.10%	0.07%	0.07%	0.03%	0.07%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.90%	6.5%
18:00	2.70%	0.88%	0.13%	0.32%	0.38%	0.13%	0.19%	0.09%	0.09%	0.06%	0.06%	0.03%	0.06%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.87%	6.3%
19:00	2.18%	0.71%	0.10%	0.26%	0.31%	0.10%	0.15%	0.08%	0.08%	0.05%	0.05%	0.03%	0.05%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.70%	5.1%
20:00	1.88%	0.61%	0.09%	0.22%	0.26%	0.09%	0.13%	0.07%	0.07%	0.04%	0.04%	0.02%	0.04%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.61%	4.4%
21:00	1.80%	0.58%	0.08%	0.21%	0.25%	0.08%	0.13%	0.06%	0.06%	0.04%	0.04%	0.02%	0.04%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.58%	4.2%
22:00	1.67%	0.54%	0.08%	0.20%	0.23%	0.08%	0.12%	0.06%	0.06%	0.04%	0.04%	0.02%	0.04%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.54%	3.9%
23:00	1.33%	0.43%	0.06%	0.16%	0.19%	0.06%	0.09%	0.05%	0.05%	0.03%	0.03%	0.02%	0.03%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%	0.43%	3.1%
	43%	14%	2.0%	5.0%	6.0%	2.0%	3.0%	1.5%	1.5%	1.0%	1.0%	0.5%	1.0%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	14%	100%

Table 13: Suggested fuel tank volumes and carbon canister sizes for the various COPERT categories (cars and light-duty vehicles).

Sector	Sub-sector	Technology	Tank volume (l)	Canister*
Car	Petrol <1.4 l	Pre-ECE	50	No
		ECE 15/00-01	50	No
		ECE 15/02	50	No
		ECE 15/03	50	No
		ECE 15/04	50	No
		Improved conventional	50	No
		Open loop	50	No
		Euro 1	50	SC
		Euro 2	50	SC
		Euro 3	50	MC
		Euro 4	50	MC
		Euro 5	50	MC
	Petrol 1.4-2.0 l	Pre-ECE	60	No
		ECE 15/00-01	60	No
		ECE 15/02	60	No
		ECE 15/03	60	No
		ECE 15/04	60	No
		Improved conventional	60	No
		Open loop	60	No
		Euro 1	60	SC
		Euro 2	60	SC
		Euro 3	60	MC
		Euro 4	60	MC
		Euro 5	60	MC
	Petrol > 2.0 l	Pre-ECE	75	No
		ECE 15/00-01	75	No
		ECE 15/02	75	No
		ECE 15/03	75	No
		ECE 15/04	75	No
		Improved conventional	75	No
		Open loop	75	No
		Euro 1	75	MC
		Euro 2	75	MC
		Euro 3	75	LC
		Euro 4	75	LC
		Euro 5	75	LC
	Hybrid petrol <1.4 l	Euro 4	50	MC
	Hybrid petrol 1.4-2.0 l	Euro 4	60	MC
	Hybrid petrol >2.0 l	Euro 4	75	LC
Light-duty vehicles	Petrol <3.5 t	Conventional	60	No
		Euro 1	60	SC
		Euro 2	60	SC
		Euro 3	60	MC
		Euro 4	60	MC
		Euro 5	60	MC

* No = no canister, SC = small canister, MC = medium canister, LC = large canister

Table 14: Suggested fuel tank volumes and carbon canister sizes for the various COPERT categories (mopeds and motorcycles).

Sector	Sub-sector	Technology	Tank volume (l)	Canister*
Mopeds	<50 cm^3	Conventional	5	No
		Euro 1	5	No
		Euro 2	5	No
		Euro 3	5	No
Motorcycles	2-stroke >50 cm^3	Conventional	8	No
		Euro 1	8	No
		Euro 2	8	No
		Euro 3	8	No
	4-stroke <250 cm^3	Conventional	10	No
		Euro 1	10	No
		Euro 2	10	No
		Euro 3	10	No
	4-stroke 250-750 cm^3	Conventional	18	No
		Euro 1	18	No
		Euro 2	18	No
		Euro 3	18	No
	4-stroke >750 cm^3	Conventional	20	SC
		Euro 1	20	SC
		Euro 2	20	SC
		Euro 3	20	SC

* No = no canister, SC = small canister

5.2.6 Calculation of diurnal emissions, hot-soak emissions and running losses

Petrol cars and light-duty vehicles

Diurnal emissions

For any parking period k the vapour generated in the tank and the associated breakthrough emissions are calculated using Equations (25)-(30) as described above. The permeation emissions are calculated by equation (32). The diurnal emissions for each parking period ***k*** (in g per parking event) are thus calculated as:

$$m_{break}(T_{1,k},T_{2,k}) + e_{perm}(T_{1,k},T_{2,k}) \qquad \text{(Equation 33)}$$

Taking into account all parking periods, the average diurnal emissions (in g day^{-1}) are calculated as:

$$e_d = \sum_k f_k \cdot (m_{break}(T_{1,k},T_{2,k}) + m_{perm}(T_{1,k},T_{2,k})) \qquad \text{(Equation 34)}$$

For petrol vehicles without carbon canister all vapour generated in the fuel tank is released in the atmosphere. Thus the mean emission factor for uncontrolled vehicles (in g day^{-1}) is given by the following equation:

$$e_d = \sum_k f_k \cdot (m_{tank}(T_{1,k},T_{2,k}) + m_{perm}(T_{1,k},T_{2,k})) \qquad \text{(Equation 35)}$$

Hot-soak emissions

For petrol vehicles with fuel injection and returnless fuel systems, the fuel temperature in the tank is not affected by engine operation and thus no fuel vapour is generated in the tank when a hot engine is turned off. Hot-soak emissions are mainly due to fuel permeation and/or leakage. Taking into account the increased temperature of the fuel circulating in the fuel system (from fuel tank to injectors), the mean hot-soak emission factor for petrol vehicles (both canister-equipped and uncontrolled) with fuel injection and returnless fuel systems (in g per procedure) is given by the following equation:

$$e_{s,hot,fi} = \sum_k f_k \cdot m_{perm}(T_{1,k} + 11) \quad \text{(Equation 36)}$$

For vehicles equipped with carburettor and/or fuel return systems, engine operation results in significant temperature increase in the fuel tank and/or the carburettor (Morgan *et al*., 1993). The additional fuel vapour that is generated loads the carbon canister causing breakthrough emissions which are calculated using equations (25)-(30) as described above. For the warm soak emissions a 4.5°C increase in the fuel temperature in the tank is used, while a 6°C increase is used for hot-soak emissions. The mean warm and hot-soak emission factors for canister-equipped petrol vehicles with carburettor and/or fuel return systems (in g per procedure) are thus given by the following equations:

$$e_{s,hot,c} = \sum_k f_k \cdot m_{break}(T_{1,k}, T_{1,k} + 6) + e_{s,hot,fi}$$
$$e_{s,warm,c} = \sum_k f_k \cdot m_{break}(T_{1,k}, T_{1,k} + 4.5) + e_{s,hot,fi} \quad \text{(Equation 37)}$$

For uncontrolled vehicles the above equations are rewritten as follows:

$$e_{s,hot,c} = \sum_k f_k \cdot m_{tank}(T_{1,k}, T_{1,k} + 6) + e_{s,hot,fi}$$
$$e_{s,warm,c} = \sum_k f_k \cdot m_{tank}(T_{1,k}, T_{1,k} + 4.5) + e_{s,hot,fi} \quad \text{(Equation 38)}$$

Running losses

As mentioned above, for vehicles with fuel injection and returnless fuel systems the fuel temperature in the tank is not affected by engine operation and thus the running losses are attributed to fuel permeation and/or leakage. The mean running losses emission factor for petrol vehicles (both canister-equipped and uncontrolled) with returnless fuel systems (in g trip^{-1}) is calculated as:

$$e_{r,hot,fi} = t_{trip} \cdot \sum_k f_k \cdot m_{perm}(T_{2,k} + 15) \quad \text{(Equation 39)}$$

where t_{trip} is the mean driving duration per trip, average over the year (h trip^{-1}).

For vehicles equipped with carburettor and/or fuel return systems, the additional fuel vapour that is generated in the fuel tank loads the carbon canister. However, the canister is being purged with air at certain time intervals and thus no significant breakthrough emissions are observed (except for long periods of idling when the purge valve, controlling the amount of air that is used for purging, remains shut). For canister-equipped vehicles with carburettor and/or fuel return systems, Equation (39) can be used for calculating hot and warm running losses, *i.e*.:

$$e_{r,hot,c} = e_{r,warm,c} = e_{r,hot,fi} \quad \text{(Equation 40)}$$

For uncontrolled vehicles the fuel vapour generated in the tank due to temperature increase also contributes to the running losses. For the warm running losses a 1°C increase in the fuel temperature in the tank is used, while a 5°C increase is used for hot running losses. The mean warm and hot running losses factors for uncontrolled petrol vehicles with fuel return systems (in g trip^{-1}) are thus given by the following equation:

$$e_{r,hot,c} = \sum_k f_k \cdot m_{tank}(T_{2,k}, T_{2,k} + 5) + e_{r,hot,fi}$$

$$e_{r,warm,c} = \sum_k f_k \cdot m_{tank}(T_{2,k}, T_{2,k} + 1) + e_{r,hot,fi} \qquad \text{(Equation 41)}$$

Two-wheel vehicles

Diurnal emissions for canister-equipped and uncontrolled two wheelers are calculated by equations (34) and (35) respectively. The mean warm and hot-soak emission factors for controlled motorcycles equipped with fuel injection and those equipped with carburettor (in g per procedure) are given by the following equations:

$$e_{s,hot,fi} = \sum_k f_k \cdot m_{break}(T_{1,k}, T_{1,k} + 1.5)$$

$$e_{s,hot,c} = \sum_k f_k \cdot m_{break}(T_{1,k}, T_{1,k} + 3.5) \qquad \text{(Equation 42)}$$

For uncontrolled mopeds and motorcycles equipped with fuel injection and those equipped with carburettor (in g per procedure) the mean warm and hot-soak emission factors are:

$$e_{s,hot,fi} = \sum_k f_k \cdot m_{tank}(T_{1,k}, T_{1,k} + 1.5)$$

$$e_{s,hot,c} = \sum_k f_k \cdot m_{tank}(T_{1,k}, T_{1,k} + 3.5) \qquad \text{(Equation 43)}$$

The mean warm and hot running losses factors for controlled motorcycles equipped with fuel injection and those equipped with carburettor (in g trip^{-1}) are given by the following equations:

$$e_{r,hot,fi} = \sum_k f_k \cdot m_{break}(T_{2,k}, T_{2,k} + 1)$$

$$e_{r,hot,c} = \sum_k f_k \cdot m_{break}(T_{2,k}, T_{2,k} + 2.5) \qquad \text{(Equation 44)}$$

For uncontrolled mopeds and motorcycles equipped with fuel injection and those equipped with carburettor the mean warm and hot running losses factors (in g trip^{-1}) are:

$$e_{r,hot,fi} = \sum_k f_k \cdot m_{tank}(T_{2,k}, T_{2,k} + 1)$$

$$e_{r,hot,c} = \sum_k f_k \cdot m_{tank}(T_{2,k}, T_{2,k} + 2.5) \qquad \text{(Equation 45)}$$

6 Model comparisons

6.1 Method

A number of basic comparisons were made between the predictions of the NAEI, ARTEMIS and COPERT 4 (Tier 2 method only) models, and the results are presented in this Chapter of the Report. The following between-model comparisons were made:

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

The assumptions used are described below. Failures of evaporative emission-control systems were not taken into account.

6.1.1 Vehicle categories

The vehicle categories used in the three models are not equivalent, and therefore several assumptions were required. For example, most pre-Euro 1 vehicles are not fitted with evaporative emission control systems, whereas vehicles from Euro 1 onwards should be fitted with controls. Furthermore, in order to calculate total annual emission factors on the same basis, correspondence with the national UK fleet data had to be established, and these are stated in terms of emission standard and engine size. For petrol cars the assumed equivalence between each model and the emission standards is shown in Table 15. To calculate the weighted emission factors the UK fleet data were taken from the NAEI website[13], although the authors believe that these data have, in fact, been superseded. For pre-Euro 1 vehicles in the COPERT 4 model a distinction is made between those equipped with a carburettor and those equipped with fuel injection. As stated in the COPERT methodology, it was assumed that 1% of pre-Euro 1 vehicles had fuel injection.

Table 15: Assumed equivalence between each model and the emission standards for petrol cars.

UK fleet data		NAEI categories[a]	ARTEMIS categories[a]	COPERT 4 categories	
Engine size	Emission standard			Fuelling	Canister size
<1.4 l	Pre-Euro 1	Uncontrolled	Pre-Euro 1 (and fail)	Carburettor	Uncontrolled
				Fuel injection	
	Euro 1	Controlled	Euro 1 & Euro 2	Fuel injection	Small
	Euro 2	Controlled			Small
	Euro 3	Controlled	Euro 3 & Euro 4		Medium
	Euro 4	Controlled			Medium
1.4-2.0 l	Pre-Euro 1	Uncontrolled	Pre-Euro 1 (and fail)	Carburettor	Uncontrolled
				Fuel injection	
	Euro 1	Controlled	Euro 1 & Euro 2	Fuel injection	Small
	Euro 2	Controlled			Small
	Euro 3	Controlled	Euro 3 & Euro 4		Medium
	Euro 4	Controlled			Medium
>2.0 l	Pre-Euro 1	Uncontrolled	Pre-Euro 1 (and fail)	Carburettor	Uncontrolled
				Fuel injection	
	Euro 1	Controlled	Euro 1 & Euro 2	Fuel injection	Medium
	Euro 2	Controlled			Medium
	Euro 3	Controlled	Euro 3 & Euro 4		Large
	Euro 4	Controlled			Large

[a] No engine size distinction is made.

[13] http://www.naei.org.uk/datachunk.php?f_datachunk_id=9

In the case of two-wheel vehicles, no emission factors are given in the NAEI and the COPERT 4 model is considerably more detailed than the ARTEMIS model. Consequently, no comparisons for these vehicles were made.

6.1.2 Ambient temperature and RVP data

In the NAEI evaporative emissions are calculated using monthly average temperature and RVP data. Calculating emissions on a monthly basis enables subtle differences in fuel volatility and differences in monthly temperature to be better accounted for. The monthly average, monthly average daily maximum, and monthly average diurnal rise in temperature are required. However, for the basic model comparison presented here, only annual average values were used. The temperature data for 2003 and beyond, and the RVP data for 2005 were used. These were supplied to TRL by UKPIA (Watson, 2007), and the values are given in Table 16.

Table 16: Temperature values for 2003 and beyond, and RVP values for 2003 and 2005.

Month	Temperature values (^{o}C) for 2003 and beyond			RVP values (kPa)
	T_{mean}	T_{rise}	T_{max}	
	2003	2003	2003	2005
January	4.7	5.15	7.29	95.0
February	5.4	5.56	8.16	95.0
March	6.9	7.97	10.84	95.0
April	8.6	8.33	12.78	90.0
May	11.7	10.06	16.71	68.0
June	14.4	10.27	19.56	68.0
July	16.7	11.24	22.31	68.0
August	16.8	11.67	22.59	68.0
September	14.0	7.87	17.9	90.0
October	10.9	7.37	14.54	95.0
November	7.4	5.74	10.25	95.0
December	4.9	4.31	7.00	95.0
Average	**10.2**	**8.0**	**14.2**	**85.2**

In the ARTEMIS model an average emission factor for running emissions for UK petrol cars was estimated by weighting the emission factors for urban, rural and motorway driving by the proportions of vehicle mileage in each road category (see Table 17).

Table 17: Distance travelled by road type, based on DfT *et al.* (2005).

Road type	Billion km	Proportion of distance
Urban	161.1	0.405
Rural	164.5	0.413
Motorway	72.6	0.182

In the case of the COPERT model, the emission factors for the summer and winter temperature ranges of 10-25^{o}C and 0-15^{o}C respectively were used.

6.2 Results

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

6.2.1 Emission factors

Diurnal emissions

The diurnal emission factors in the three models are all stated in g vehicle^{-1} day^{-1}. These emission factors are shown in Figure 2. Vehicles without evaporative emission-control systems exhibit substantially higher diurnal emissions than controlled vehicles. However, the majority of vehicles on UK roads now contain such controls, and therefore uncontrolled emissions are gradually becoming less important as these vehicles are phased out.

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

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

Hot-soak emissions

The hot-soak emission factors in the three models - stated in g vehicle^{-1} trip^{-1} - are shown in Figure 3. Again, the emission factors for uncontrolled vehicles are much higher than those for controlled vehicles.

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

Running emissions

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

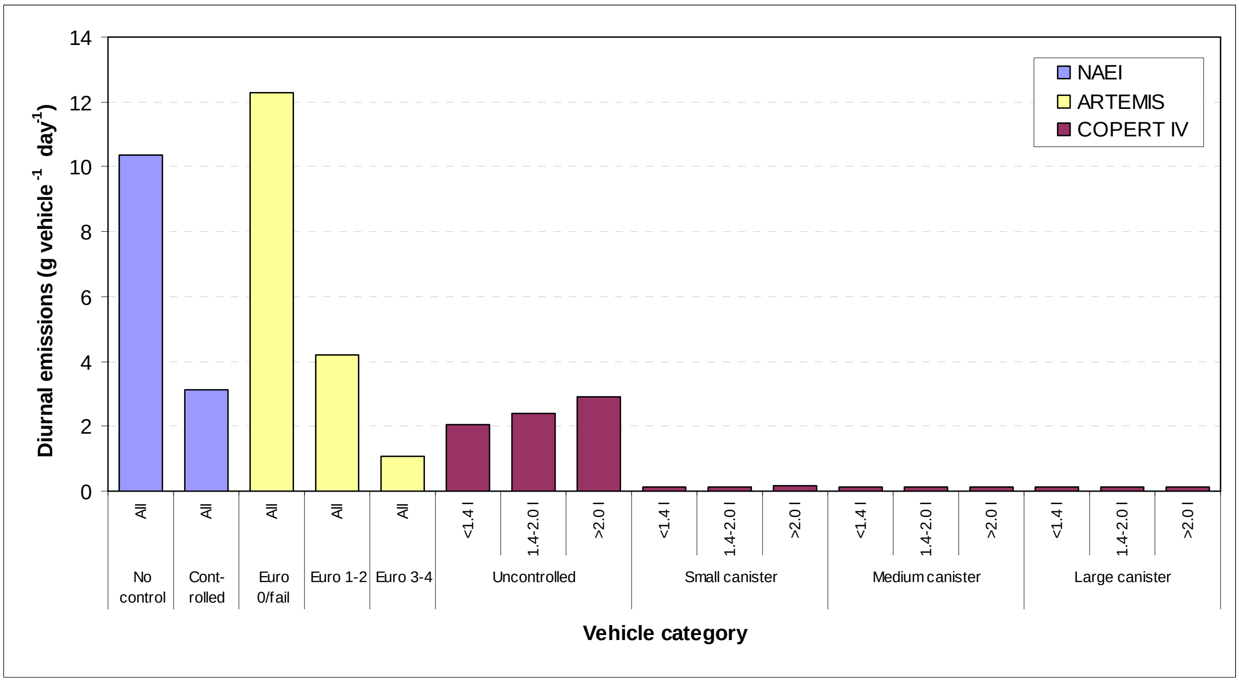

Figure 2: Diurnal emission factors in the NAEI, ARTEMIS and COPERT 4 methods.

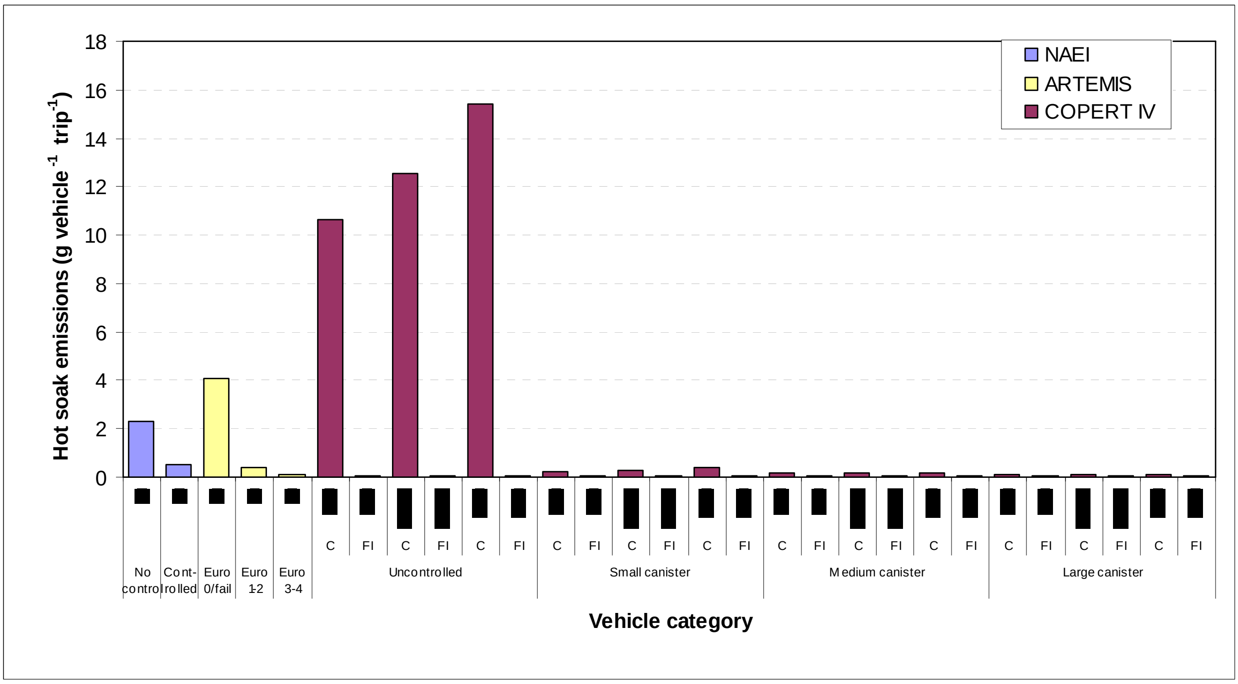

Figure 3: Hot soak emission factors in the NAEI, ARTEMIS and COPERT 4 methods (COPERT 4 also includes 'cold and warm soak' for vehicles with a carburettor). C = carburettor, FI = fuel injection.

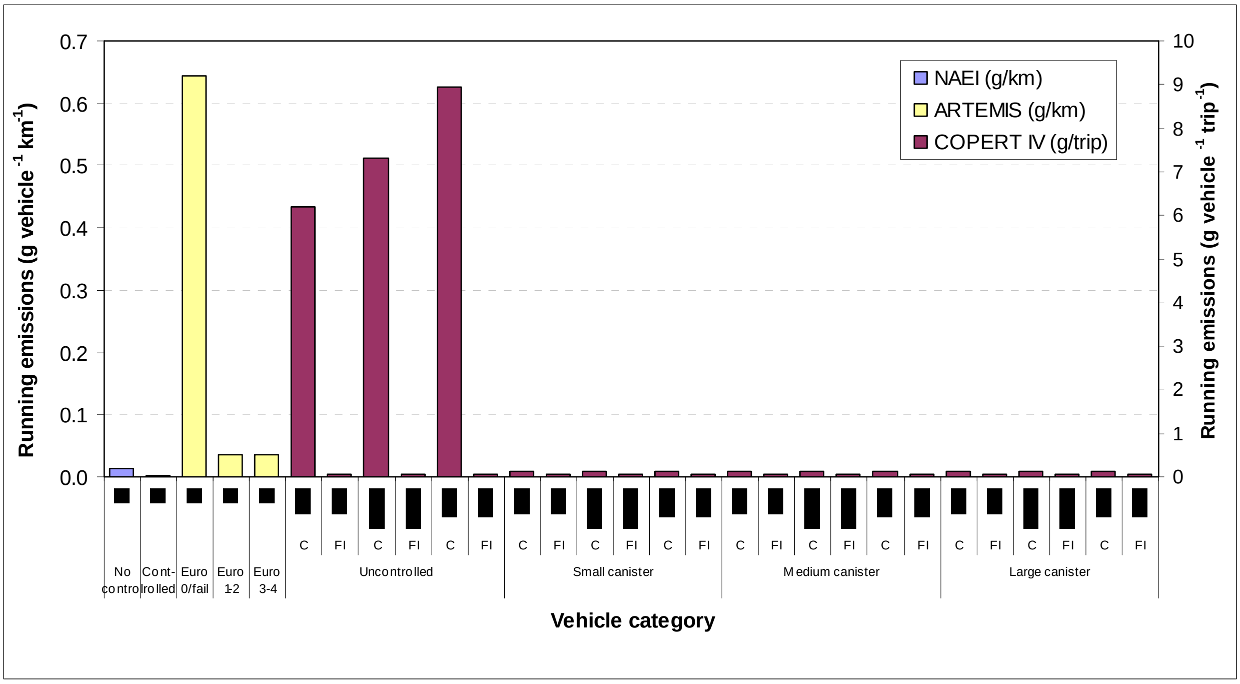

Figure 4: Running emission factors in the NAEI, ARTEMIS and COPERT 4 methods (COPERT 4 also includes 'cold and warm running' for vehicles with a carburettor). C = carburettor, FI = fuel injection.

6.2.2 Fleet-weighted emission factors

The diurnal, hot-soak and running emission factors were combined by weighting the emission factors for each vehicle category according to the composition of the 2007 fleet, and converting the three sources into annual mass emissions. This was achieved, in the case of hot-soak emissions (and running emissions in the case of COPERT 4), by multiplying the emissions per trip by the annual number of trips. The number of trips per year was obtained by dividing the average annual distance travelled (assumed to be 10,000 miles) by the average trip length. Running emissions were converted by multiplying by the average annual distance travelled. The average distance per year for petrol cars was provided by Li (2006), and the average petrol car trip length was based on data for 1999-2001 (DfT, 2003). The overall results are shown in Figure 5.

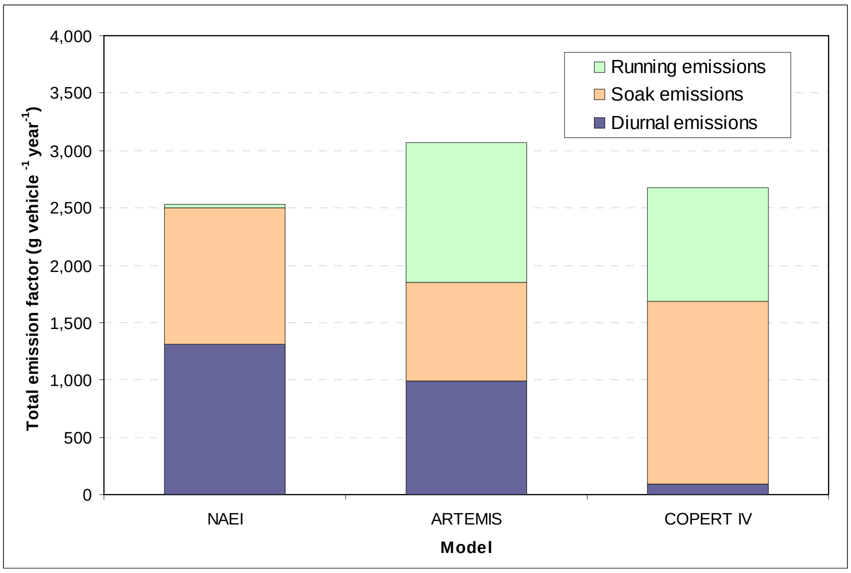

Figure 5: Fleet-weighted annual emission factors in the NAEI, ARTEMIS and COPERT 4 methods.

It can be seen that the total fleet-weighted annual emission factors in the three models are rather similar, ranging from around 2.5 kg vehicle^{-1} year^{-1} to around 3 kg vehicle^{-1} year^{-1}. This is in spite of the fact that the relative contributions of diurnal, hot soak and running emissions in the three models are very different. In particular, running emissions in the NAEI, and diurnal emissions in COPERT 4, are very low compared with the other models.

7 Findings of the EUCAR/JRC/CONCAWE research programme

One of the measures envisaged by the EU in the field of energy and transport is the promotion of biofuels. Directive 2003/30/EC - the 'Biofuels Directive' - was agreed by the European Council and Parliament on 8 May 2003. The main objectives of the Directive are to reduce life-cycle emissions of carbon dioxide from transport across Europe, and to reduce the EU's future reliance on external energy sources (in this case, oil). The Directive aims to promote the use of biofuels, or other renewable fuels, as substitutes for petrol or diesel in the transport sector. It requires Member States to take account of the reference values prescribed in Article 3(1) in setting their national indicative targets. These reference values are:

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

The term 'biofuel' is a generic one used to describe liquid or gas fuels which are either not derived from fossils fuels or contain a proportion of non-fossil fuel. Biofuels fall into two main categories: conventional biofuels produced from plants (crops such as sugar cane/beet and wheat for ethanol, and rape seed oil or re-processed vegetable oils for biodiesel), and advanced biofuels from gasified biomass. At present, most biofuels fall into the conventional category. Although biofuels can be used as road fuels on their own, mostly they are blended with conventional petrol or diesel fuel. Directive 2003/17/EC currently limits the biofuel content of conventional petrol and diesel to 5% by volume[14]. Ethanol and biodiesel are at the moment the only biofuels available in sufficient quantity that can allow the achievement of these targets.

CONCAWE, EUCAR and the Joint Research Centre of the European Commission carried out a major test programme specifically designed to investigate the influence of petrol vapour pressure and ethanol content on evaporative emissions from modern passenger cars, as determined using the current European regulatory test procedure (Martini *et al*., 2007). The main objectives of the programme were the following:

- To assess the effects of ethanol content and vapour pressure on evaporative emissions, as determined using the current European test procedure from a range of latest generation canister-equipped petrol cars.
- To provide a technical basis for discussion on petrol vapour pressure limits in relation to ethanol blending for a review of the Fuels Directive (98/70/EC).

When blended with petrol, ethanol is known to cause an increase in the vapour pressure compared with the base petrol. As a consequence of the European policy aiming to promote the use of ethanol and other biofuels, the question has arisen whether the vapour pressure limit for ethanol/petrol blend should be relaxed with respect to the current fuel specifications laid down in Directive 98/70/EC. The programme was conceived specifically to assess the effect of ethanol/petrol blends on evaporative emissions.

DVPE was measured according to the EN 13016-1 method. CEN standard EN 228:2004 sets out the petrol volatility classes applied in Europe. Class A (maximum DVPE of 60 kPa) is required by the Fuels Directive during summer (1 May to 30 September), and Class B (maximum DVPE of 70 kPa) is required for countries 'with arctic Conditions' from 1 June to 31 August.

Seven petrol passenger cars - representative of current Euro 3-4 technology - were tested for evaporative emissions using 10 different test fuels. The test fuel matrix comprised 60 kPa and 70 kPa fuels with 5% and 10% ethanol 'splash'[15] blends, and 5% and 10% ethanol 'matched volatility'[16] blends. The evaporative emission tests were carried out according to a test protocol agreed by the partners of the programme, and based on the European homologation test procedure.

The test procedure was found to have a considerable influence on the results. In particular, repeating the test procedure, without any additional conditioning between tests above that prescribed by the legislation, resulted

[14] http://www.ukpia.com/industry_issues/fuels/alternative_fuels.aspx?referrertabid=2107&linktext=Alternative+Fuels
[15] Conventional petrol blended directly with ethanol, which increases fuel volatility.
[16] Specially tailored petrol blended with ethanol to account for increased fuel volatility.

in an increase of the carbon canister weight with successive tests. In other words, the test protocol was not able to return the vehicle to a consistent condition at the start of each test. The increase of the canister weight, which was indicative of the accumulation of petrol/ethanol vapours probably due to insufficient canister purging, may not represent real-world operating conditions as the canister load depends on typical driving patterns. Running at these increased canister weights is a very severe test of the evaporative control system. The canister weight problem made it more difficult both to obtain representative emission measurements from the various vehicles and to clearly determine fuel effects (Martini *et al*., 2007).

The test vehicles differed in their level of evaporative emissions and in the extent of their response to fuel changes.

The test results confirmed that vapour pressure is a key fuel variable for evaporative emissions. In general, increasing the fuel vapour pressure above 60 kPa increased evaporative emissions. However the effect of vapour pressure is strongly non-linear, as expected for a process in which a vapour breakthrough effect may occur. The ethanol blends with final DVPE around 75 kPa gave considerably higher evaporative emissions than the other lower volatility fuels in most of the vehicles. Differences between fuels with DVPE in the range 60-70 kPa were small. Furthermore, due to the combination of DVPE variations, the presence or absence of ethanol, and to significant changes of canister weight, no reliable conclusions could be drawn on the influence of individual parameters. The results obtained in a few tests where extra purging of the canister was carried out suggested that differences in evaporative emission measurements on fuels in this volatility range could be reduced if a more extensive canister conditioning procedure was adopted.

Ethanol might also influence evaporative emissions via different mechanisms than the increased vapour pressure of ethanol/petrol blends. For example ethanol is known to be difficult to purge from carbon canisters, and could reduce their working capacity. To explore this possibility ethanol/petrol blends matching the vapour pressure of the pure hydrocarbon base fuel were included in the fuel matrix. The increase in canister loading noticed during the programme could be due to increased adsorption of hydrocarbons or ethanol in the canister, or both, but the poor repeatability of the main data set did not allow the relative sizes of these effects to be quantified. However multiple additional tests on one vehicle showed that ethanol containing fuels with matched volatility gave higher emissions than the hydrocarbon fuels. Ethanol was also found in the SHED vapour of tests on pure hydrocarbon fuels following use of ethanol-containing fuels. Further research would be required to clarify these effects.

Extra diurnal emission tests were carried out on two vehicles with the canister vented outside of the SHED. The results of these tests suggest that fuel permeation through plastics and rubbers could be a significant contributor to evaporative emissions.

The data showed that volumetric fuel consumption (litres per 100 km) increased with increasing ethanol content. This increase was roughly proportional to the oxygen content of the fuel. However there was no effect of ethanol on energy consumption.

The test programme was designed to explore only the effects of ethanol and fuel vapour pressure on evaporative emissions from a range of latest generation canister-equipped petrol cars using the EU Evaporative Emissions test procedure. Other parameters like test temperature profile, presence of ethers in the fuel, fuel permeation and the long term effect of ethanol and water on carbon canister working capacity were not addressed.

Although the work has provide a large amount of new information on evaporative emissions, no new model for use in inventories was developed. However, additional measurements were conducted for inclusion in COPERT 4.

8 Summary, conclusions and recommendations

8.1 Summary

8.1.1 Background

Evaporative emissions of VOCs constitute a significant fraction of total VOCs emitted from road transport. However, in spite of the tightening of emission standards, improvements in vehicle technology, and petrol regulations, the problem of evaporative emissions remains. This is mainly a result of the continuing presence of older, uncontrolled vehicles, vehicles with defective evaporative control systems, motorcycles, petrol power tools and a variety of recreational vehicles.

Most evaporative emissions of VOCs emanate from the fuel systems (tanks, injection systems and fuel lines) of petrol vehicles. Evaporative emissions from petrol vehicles consist mainly of light hydrocarbons. Evaporative emissions from diesel vehicles are considered to be negligible due to the presence of heavier hydrocarbons and the extremely low volatility of diesel fuel. There are five mechanisms by which petrol fuel evaporates from vehicles:

- Diurnal emissions
- Hot-soak emissions
- Running emissions
- Resting Emissions
- Refuelling emissions

Evaporative emissions from motor vehicles are dependent upon four major factors:

- The vehicle and fuel system design.
- The ambient temperature, and its temporal variation.
- The petrol volatility - usually expressed by the empirical fuel parameter known as Reid vapour pressure (RVP).
- Driving conditions (trip length, parking time, *etc.*).

Evaporative emissions are not easily controlled due to the fact that venting of the vehicle tank system must be provided so it can ‘breathe’ during temperature changes. In the past, fuel vapours were simply vented into the atmosphere. Nowadays, the control of evaporative emissions can be achieved via the control of fuel properties and by vehicle technology.

8.1.2 Evaporative emission models

The emission factors and method currently used in the NAEI to determine evaporative emissions are rather old and are due for revision. The NAEI approach for evaporative emissions is based largely on the COPERT II and COPERT III models, combined with supporting experimental data from before 1995. However, within the last decade few measurements of evaporative emissions have been made in Europe, and therefore models have not been updated. The most significant recent measurements and model developments have been the following:

- The European Commission’s Fifth Framework project ARTEMIS.
- The EUCAR/JRC/CONCAWE joint programme on evaporative emissions from petrol cars.
- A draft version of the COPERT 4 model.

Comparisons between the NAEI model, the ARTEMIS model, and the COPERT 4 model were undertaken.

All three models showed that vehicles without evaporative emission-control systems exhibit substantially higher diurnal emissions than controlled vehicles. However, the majority of vehicles on UK roads now contain such controls, and therefore uncontrolled emissions are gradually becoming less important as these vehicles are phased out.

All three models use a different system of vehicle categorisation, with ARTEMIS and COPERT 4 providing more detail than the NAEI model. This allows more in-depth assessments to be made, and allows the reasons for differences in total emissions to be better understood. The NAEI method could therefore be further refined by introducing a more detailed vehicle classification system for evaporative emissions.

The emission factor for diurnal emissions from pre-Euro 1 petrol cars in the ARTEMIS model is around 20% higher that that for uncontrolled vehicles in the NAEI. For Euro 1 and Euro 2 vehicles, the ARTEMIS emission factors is around 35% higher than that for uncontrolled vehicles in the NAEI. However, the ARTEMIS emission factor for Euro 3 and 4 vehicles is much lower than that for controlled vehicles in the NAEI. The diurnal emission factors in COPERT 4 are much lower than those in ARTEMIS and the NAEI.

The ARTEMIS model predicts that pre-Euro 1vehicles have 80% higher hot-soak emissions than the equivalent uncontrolled category in the NAEI. For controlled vehicles ARTEMIS has lower emission factors. COPERT 4 has higher hot-soak emission factors than the other models for uncontrolled vehicles, but the emission factors for controlled vehicles are of a similar magnitude to those for Euro 3 and 4 vehicles in ARTEMIS. It should be noted that COPERT 4 also includes ‘cold and warm soak’ for vehicles with a carburettor. If these are excluded, the COPERT emission factors are reduced by around 40-50%, but are still higher than those in the other models.

Both the ARTEMIS and COPERT emission factors for running emissions are considerably higher than those used in the NAEI.

The total fleet-weighted annual emission factors in the three models are rather similar, ranging from around 2.5 kg vehicle^{-1} year^{-1} to around 3 kg vehicle^{-1} year^{-1}. This is in spite of the fact that the relative contributions of diurnal, hot soak and running emissions in the three models are very different. In particular, running emissions in the NAEI, and diurnal emissions in COPERT 4, are very low compared with the other models.

In view of the large discrepancies between the predictions of running and diurnal emissions, there is a case for examining these sources in more detail and, if necessary, performing further validation tests. However, running emissions may be heavily dependent upon the condition of the vehicle (*i.e.* whether it has leaks in the fuel system, lubrication or exhaust system which could be detected during a SHED test, and obtaining a reliable statistical sample may be difficult and expensive.

It is also noted that vehicles which have failures in the evaporative emissions-control system are classed as having pre-Euro 1 evaporative emission levels in the ARTEMIS model. Although failures were not specifically addressed in this work it is more likely that failures are partial, and that this assumption is too severe.

8.1.3 Findings of the EUCAR/JRC/CONCAWE research programme

CONCAWE, EUCAR and the Joint Research Centre of the European Commission jointly carried out a major test programme specifically designed to assess the effects of ethanol content and vapour pressure on evaporative emissions.

The test procedure was found to have a considerable influence on the results. In particular, repeating the test procedure, without any additional conditioning between tests above that prescribed by the legislation, resulted in an increase of the carbon canister weight with successive tests. The canister weight problem made it more difficult both to obtain representative emission measurements from the various vehicles and to clearly determine fuel effects

The test results also confirmed that vapour pressure is a key fuel variable for evaporative emissions. In general, increasing the fuel vapour pressure above 60 kPa increased evaporative emissions. However the effect of vapour pressure is strongly non-linear, as expected for a process in which a vapour breakthrough effect may occur. The ethanol blends with final DVPE around 75 kPa gave considerably higher evaporative emissions than the other lower volatility fuels in most of the vehicles. Differences between fuels with DVPE in the range 60-70 kPa were small. Furthermore, due to the combination of DVPE variations, the presence or absence of ethanol, and to significant changes of canister weight, no reliable conclusions could be drawn on the influence of individual parameters. The results obtained in a few tests where extra purging of the canister was carried out suggested that differences in evaporative emission measurements on fuels in this volatility range could be reduced if a more extensive canister conditioning procedure was adopted.

Multiple tests on one vehicle showed that ethanol containing fuels with matched volatility gave higher emissions than the hydrocarbon fuels. Other tests suggest that fuel permeation through plastics and rubbers could be a significant contributor to evaporative emissions.

The test programme was designed to explore only the effects of ethanol and fuel vapour pressure on evaporative emissions from a range of latest generation canister-equipped petrol cars using the EU Evaporative Emissions test procedure. Other parameters like test temperature profile, presence of ethers in the fuel, fuel permeation and the long term effect of ethanol and water on carbon canister working capacity were not addressed.

8.2 Conclusions and recommendations

The main conclusion of this work is that, given that considerable effort has be put into developing the new method in COPERT 4 and the flexibility it offers, there would be sufficient justification for changing the NAEI to include this method. This Report has only examined the Tier 2 version of COPERT 4. Further work is required to assess the applicability and reliability of the detailed Tier 3 method in COPERT 4. This work was considered to be beyond the scope of this report.

Allowance should also be made in the NAEI for the failure of evaporative control systems. Again, the detailed method of COPERT 4 allows for this. However, there is little or no information on the actual proportion of in-service vehicles in the UK which have failures. This is an area which requires further investigation.

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Appendix A: Abbreviations and terms used in the Task Reports

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

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

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

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

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

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