A review of instantaneous emission models for road vehicles

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

PPR 267

PUBLISHED PROJECT REPORT
A REVIEW OF INSTANTANEOUS EMISSION MODELS FOR ROAD VEHICLES

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

Prepared for: Project Record: Framework Contract no. 3/323-R041
SCOPING STUDY ON THE POTENTIAL FOR INSTANTANEOUS EMISSION MODELLING

Client: Highways Agency
(Michele Hackman)

Copyright Transport Research Laboratory, August 2007.

This report has been prepared for the Highways Agency. The views expressed are those of the authors and not necessarily those of the Highways Agency.
If this report has been received in hard copy from TRL, then in support of the company’s environmental goals, it will have been printed on recycled paper, comprising 100% post-consumer waste, manufactured using a TCF (totally chlorine free) process.

**Contents Amendment Record**

This report has been issued and amended as follows

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Description</th>
<th>Editor</th>
<th>Technical referee</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPR/IE/030/06,</td>
<td>May 2006</td>
<td>Unpublished, approval</td>
<td>P G Boulter</td>
<td>I S McCrae</td>
</tr>
<tr>
<td>version 1.1,</td>
<td></td>
<td>version</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final</td>
<td>3 August 2007</td>
<td>PPR 267</td>
<td>P G Boulter</td>
<td>I S McCrae</td>
</tr>
</tbody>
</table>
Executive summary

TRL was commissioned by the Highways Agency (HA) to assess the scientific understanding of ‘instantaneous’ emission models for road vehicles. An understanding of emissions will ultimately assist the HA to better target mitigation measures and to develop cost-effective policies for reducing ambient pollutant concentrations in the vicinity of the UK trunk road network. The overall aims of the research are to review and evaluate instantaneous emission data and models, and to show how improvements in modelling could lead to improvements in the prediction and control of local air quality. The project is divided into four main Tasks. Task 1 is a review of existing instantaneous emission models for road vehicles. Task 2 is a model evaluation and inter-comparison exercise. Task 3 is an examination of the links between instantaneous emission models, traffic models and air pollution models, and Task 4 will develop recommendations for model application and future research.

This Report, which is the result of Task 1 of this project, presents a review of existing models. The review explains the rationale of instantaneous emission modelling, and describes a number of models in some detail, with reference to aspects such as availability, cost, capabilities, ease of use and the robustness of the predictions. The review covers emission models which have been available for some time, as well as those from recent and on-going research programmes. For example, a substantial amount of work has recently been conducted in the European Commission’s 5th Framework ARTEMIS and DECADE projects. Although the emphasis is on European models, as these are relevant to UK vehicles, some consideration is given to the approaches and models developed outside Europe, such as the USEPA MOVES model.

The review deals principally with ‘hot’ exhaust emissions, as most of the instantaneous modelling research deals with this topic. Other sources, which are not normally modelled on an instantaneous basis and are therefore not discussed in detail in this Report, include cold-start exhaust emissions and the generation of particles via non-exhaust processes such as tyre wear and brake wear.

Instantaneous emission models aim to provide a precise description of vehicle emission behaviour by relating emission rates to vehicle operation during a series of short time steps (often one second). In principle, instantaneous models allow the user to calculate emissions for any vehicle operation profile, and therefore new emission factors can be generated without the need for further testing. The models inherently take into account the dynamics of driving cycles, and can therefore be used to explain some of the variability in emissions associated with given average speeds. Furthermore, instantaneous models allow emissions to be resolved spatially, and thus have the potential to lead to improvements in the prediction of air pollution. However, in order to apply instantaneous models detailed and precise measurements of vehicle operation and location are required, otherwise any potential benefits may be lost. This is likely to be rather difficult for many model users, as such information is relatively expensive to collect. As a consequence, the use of instantaneous models has mainly been restricted to the research community.

The complexity of instantaneous models has increased during the last 10 to 15 years. Some instantaneous models, especially the older models, relate fuel consumption and/or emissions to vehicle speed and acceleration during a driving cycle. Other models use some description of the engine power requirement. However, there are a number of fundamental problems associated with the development of instantaneous models. It is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and then it is not straightforward to allocate the emission values to the correct operating conditions. During measurement in the laboratory, an emission signal is dynamically delayed and smoothed, and this makes it difficult to align the emissions signal with the vehicle operating conditions. Until recently, such distortions have not been taken into account in instantaneous models. In the review the term ‘unadjusted’ has been used to refer to models in which no adjustments are made to the emission signals to account for dynamic distortion during measurement. Conversely, the term ‘adjusted’ has been used to describe models which do attempt to address the distortion.

Progress has clearly being made towards the accurate modelling of emissions from individual vehicles on a continuous basis, with an emphasis being placed on obtaining the ‘correct’ emission values at the exhaust pipe.
However, in terms of their applicability instantaneous models still face a number of challenges. Firstly, as the effort required to model emissions from the newest vehicles on an instantaneous basis is increasing, the actual emission levels are decreasing. Given the cost of model development and application, this raises the question of whether instantaneous modelling is ultimately worthwhile. In addition, it is possible that the process of averaging over many vehicles to obtain representative emission estimates could obscure any improvements in accuracy associated with using a detailed model. Therefore, the possible advantages of instantaneous models need to be investigated in more detail, and this will be the main objective of subsequent phases of the project.
Contents

1 Introduction
   1.1 Background and project objectives
   1.2 Emission modelling approaches
      1.2.1 Aggregated emission factor models
      1.2.2 Average speed models
      1.2.3 ‘Corrected’ average speed models
      1.2.4 Traffic situation models
      1.2.5 Multiple linear regression models
      1.2.6 Modal models
   1.3 Report structure

2 ‘Unadjusted’ models based on speed and acceleration
   2.1 MODEM
      2.1.1 Background
      2.1.2 Modelling approach
      2.1.3 Validation
      2.1.4 Software description
   2.2 Digitised Graz Model
      2.2.1 Background
      2.2.2 Modelling approach
      2.2.3 Validation
      2.2.4 Software description

3 ‘Unadjusted’ models based on engine power demand
   3.1 PHEM (HDV part)
      3.1.1 Background
      3.1.2 Modelling approach
      3.1.3 Validation
      3.1.4 Software description
   3.2 VeTESS
      3.2.1 Background
      3.2.2 Modelling approach
      3.2.3 Validation
      3.2.4 Software description
   3.3 CMEM
      3.3.1 Background
      3.3.2 Modelling approach
      3.3.3 Validation
      3.3.4 Software description
   3.4 ADVISOR
      3.4.1 Background
      3.4.2 Modelling approach
   3.5 MOVES
      3.5.1 Background

4 ‘Adjusted’ models
   4.1 Background
      4.1.1 Modelling errors
1 Introduction

1.1 Background and project objectives

TRL has been commissioned by the Highways Agency (HA) to assess the scientific understanding of ‘instantaneous’ emission models for road vehicles. An understanding of emissions helps HA to better target mitigation measures and to develop cost-effective policies for reducing ambient pollutant concentrations in the vicinity of the UK trunk road network.

The overall aims of the research are to review and evaluate instantaneous emission data and models, and to show how improvements in modelling could lead to improvements in the prediction and control of local air quality. The project is divided into four main Tasks:

- Task 1: A review of existing instantaneous emission models for road vehicles.
- Task 2: A model evaluation and inter-comparison exercise.
- Task 3: An examination of the links between instantaneous emission models, traffic models and air pollution models.
- Task 4: Recommendations for model application and future research.

This Report presents the findings of Task 1. The review explains the rationale of instantaneous emission modelling, and describes a number of models in some detail, with reference to aspects such as availability, cost, capabilities, ease of use and the robustness of the predictions. The review covers emission models which have been available for some time, as well as those from recent and on-going research programmes. For example, a substantial amount of work has recently been conducted in the European Commission’s 5th Framework ARTEMIS\(^1\) and DECADE\(^2\) projects. Although the emphasis is on European models, as these are relevant to UK vehicles, some consideration is given to the approaches and models developed outside Europe.

The review deals principally with ‘hot’\(^3\) exhaust emissions, as most of the instantaneous modelling research deals with this topic. Other sources, which are not normally modelled on an instantaneous basis and are therefore not discussed in detail in this Report, include cold-start exhaust emissions and the generation of particles via non-exhaust processes such as tyre wear and brake wear.

In order to understand the reasons for the development of instantaneous models, it is helpful to refer to other modelling approaches and to highlight their relative advantages and disadvantages. Hence, the next Section of this introductory Chapter summarises different types of model, with a view to placing instantaneous models into context.

In the measurement and modelling of vehicle emissions, a number of different abbreviations and terms are often used to describe similar concepts or activities. Appendix A provides a list of abbreviations and a glossary which explains how specific terms are used in the context of this report.

1.2 Emission modelling approaches

A range of atmospheric pollutants are emitted from road vehicles as a result of combustion and other processes. The main sources of emissions, and the pollutants concerned, are summarised in Table 1. Exhaust emissions of carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NO\(_x\)) and particulate matter (PM) are regulated by EU Directives, as are evaporative emissions of VOCs. A range of unregulated gaseous pollutants are also emitted, including the greenhouse gases carbon dioxide (CO\(_2\)), methane (CH\(_4\)) and nitrous oxide (N\(_2\)O). However, with the exception of CO\(_2\), unregulated pollutants have been characterised in less detail than the regulated ones. Emission levels are dependent upon many parameters, including vehicle-related factors such as model, size, fuel type, technology level and mileage, and operational factors such as speed, acceleration, gear selection, road gradient and ambient temperature.

\(^{1}\) http://217.118.140.155/artemis/
\(^{2}\) http://www.cle.de/umwelt/decade/index.html
\(^{3}\) Emissions produced when the engine and catalyst are at their full operational temperatures.
Table 1: Vehicle emission sources and pollutants.

<table>
<thead>
<tr>
<th>Source/process</th>
<th>Pollutant(s) emitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulated pollutants</td>
<td>CO, VOCs, NOx, PM</td>
</tr>
<tr>
<td>Hot and cold-start exhaust emissions</td>
<td></td>
</tr>
<tr>
<td>Unregulated pollutants</td>
<td>PM (unregulated)</td>
</tr>
<tr>
<td>Evaporative emissions</td>
<td>VOCs (regulated)</td>
</tr>
<tr>
<td>Tyre and brake wear</td>
<td></td>
</tr>
<tr>
<td>Road surface wear</td>
<td></td>
</tr>
<tr>
<td>Resuspension</td>
<td></td>
</tr>
</tbody>
</table>

In some European countries estimates of road transport emissions have been made on a national basis, and more locally as part of pollution impact studies, since the 1970s. The methods used have been improved and developed since then, mainly depending on the amount, type and quality of data available (European Commission, 1999). All emission models must take into account the various factors affecting emissions, although the manner and detail in which they do so can differ substantially. Models for estimating emissions from road vehicles can be classified in several different ways, and classification systems tend to be based upon a combination of the geographical scale of application, the generic model type, or the nature of the emission calculation approach. A distinction can also be made between models which use continuous emission functions and models which use discrete emission values. These different classification systems, with examples of specific models, are summarised in Table 2. Explanations of the model acronyms are provided in Appendix A, and the generic types of model are discussed in more detail in the following paragraphs.

Table 2: Models for estimating emissions from light-duty vehicles.

<table>
<thead>
<tr>
<th>Generic type</th>
<th>Example</th>
<th>Type of emission factor/function</th>
<th>Type of input data</th>
<th>Typical application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregated emission factors</td>
<td>NAEI</td>
<td>Discrete, trip-based</td>
<td>Road type</td>
<td>Emission inventories, EIA(^5), SEA(^6)</td>
</tr>
<tr>
<td>Average speed</td>
<td>COPERT, DMRB</td>
<td>Continuous, trip- or link-based</td>
<td>Average trip speed</td>
<td>Emission inventories, dispersion modelling</td>
</tr>
<tr>
<td>Adjusted average speed</td>
<td>TEE</td>
<td>Continuous, link-based</td>
<td>Average speed, congestion level</td>
<td>Emission inventories, dispersion modelling</td>
</tr>
<tr>
<td>Traffic situation</td>
<td>HBEFA</td>
<td>Discrete, link-based</td>
<td>Road type, speed limit, level of congestion</td>
<td>Inventories, EIA, SEA, area-wide assessment of urban traffic management schemes, dispersion modelling</td>
</tr>
<tr>
<td>Multiple linear regression</td>
<td>VERSIT+</td>
<td>Discrete, link-based</td>
<td>Driving pattern</td>
<td>Emission inventories, dispersion modelling</td>
</tr>
<tr>
<td>‘Simple’ modal</td>
<td>UROPOL</td>
<td>Discrete, link-based</td>
<td>Distribution of driving modes</td>
<td>Local assessment of urban traffic management schemes</td>
</tr>
<tr>
<td>Instantaneous – speed based</td>
<td>MODEM, DGV</td>
<td>Discrete, trip-based</td>
<td>Driving pattern</td>
<td>Detailed temporal and spatial analysis of emissions, dispersion modelling</td>
</tr>
<tr>
<td>Instantaneous – power based</td>
<td>VeTESS, PHEM</td>
<td>Discrete, trip-based</td>
<td>Driving pattern, gradient, vehicle data</td>
<td>Detailed temporal and spatial analysis of emissions, dispersion modelling</td>
</tr>
</tbody>
</table>

\(^4\) Most of the models listed also address other types of vehicle, such as heavy goods vehicles and buses.

\(^5\) EIA = environmental impact assessment.

\(^6\) SEA = strategic environmental assessment.
1.2.1 Aggregated emission factor models

Aggregated emission factor models operate on the simplest level, with a single emission factor being used to represent a particular type of vehicle and a general type of driving – the traditional distinction is between urban roads, rural roads and motorways. Vehicle operation is therefore only taken into account at a very rudimentary level, and the approach cannot be used to determine emissions for situations which are not explicitly defined. The emission factors are calculated as mean values of measurements on a number of vehicles over given driving cycles, and are usually stated in terms of the mass of pollutant emitted per vehicle and per unit distance (g vehicle\(^{-1}\) km\(^{-1}\)) or per unit of fuel consumed (g litre\(^{-1}\)). Given their simplicity, these factors are of most use in applications on a large spatial scale, such as national and regional emissions inventories, where little detailed information on vehicle operation is required.

1.2.2 Average speed models

Average-speed emission functions for road vehicles are also widely applied in regional and national inventories, but are currently used in a large proportion of local air pollution prediction models. The average-speed approach is exemplified by the model incorporated within the UK Design Manual for Roads and Bridges (DMRB) (Highways Agency et al., 2003) and the European Environment Agency’s COPERT III model (Ntziachristos and Samaras, 2000). Average-speed models are based upon the principle that the average emission factor for a certain pollutant and a given type of vehicle varies according to the average speed during a trip. The emission factor is again usually stated in grammes per vehicle-kilometre (g vehicle\(^{-1}\) km\(^{-1}\)). Figure 1 shows how a continuous average-speed emission function is fitted to the emission factors measured for several vehicles over a range of driving cycles, with each cycle representing a specific type of driving, including stops, starts, accelerations and decelerations.

![Figure 1: Average speed emission function (red line) for NO\(_x\) emissions from Euro III diesel cars <2.0 litres. The blue points show the underlying emission measurements (Barlow et al., 2001).](image)

A number of factors have contributed the widespread use of average-speed approach. For example, it is one of the oldest approaches, the models are comparatively easy to use, and there is a reasonably close correspondence between the required model inputs and the data generally available to users. In principle, the input is the trip-based average speed, although in practice it is also common for local speed measurements taken at discrete locations to be used. However, there are now considered to be a number of limitations associated with average-speed models, including the following:
(i) Trips having very different vehicle operation\(^7\) characteristics, and therefore different emission levels, can have the same average speed. Clearly, all the types of operation associated with a given average speed cannot be accounted for by the use of a single emission factor. This is less of a problem at higher average speeds, for which the possible variations in vehicle operation are more limited, but at lower average speeds the range of possible operational conditions associated with a given average speed is much greater.

(ii) In response to the tightening of emission control legislation, vehicles have been equipped with increasingly sophisticated after-treatment devices. For modern catalyst-equipped vehicles a large proportion of the total emission during a trip can be emitted as very short, sharp peaks, often occurring during gear changes and periods of high acceleration. The use of after-treatment devices, manufacturer-specific engine management software, and regenerating after-treatment systems also make it much more difficult to predict emissions. Average speed has therefore become a less reliable indicator for the estimation of emissions for the newest generation of vehicles; the average speed model provides an impression of reality that is often too simplistic.

(iii) The shape of an average speed function is not fundamental, but depends on, amongst other factors, the types of cycle used in development of the functions. For example, each cycle used in the development of the functions typically represents a given real-world driving condition, but the real distribution of these driving conditions is not normally taken into account (\(e.g.\) via weightings).

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

One of the limitations of average speed models mentioned earlier was the inability to account for the ranges of vehicle operation and emission behaviour which can be observed for a given average speed. In this context the concept of ‘cycle dynamics’ has become useful for emission model developers (\(e.g.\) Sturm et al., 1998).

In qualitative terms, cycle dynamics can be thought of as the ‘aggressiveness’ of driving, or the extent of ‘transient\(^8\)’ operation in a driving pattern. Quantitatively, the term refers to the variation in various properties or statistical descriptors of a vehicle operation pattern. Researchers have examined a range of variables in an attempt to understand the links between cycle dynamics and emissions. As the vehicle operation information available to model users and developers has tended to be very limited, and almost invariably speed-based (\(e.g.\) spot speeds measured using traffic counting equipment), interest has inevitably focussed on parameters which describe speed variation in some way. Some of the more useful parameters appear to be relative positive acceleration (Ericsson, 2000) and positive mean acceleration (Osses et al., 2002). However, there are even problems with this simplest concept of cycle dynamics, for example:

(i) Most model users have little or no straightforward means of relating to descriptors of variation in vehicle operation, as these describe the properties of entire driving patterns (of course, this does not only affect speed). Most model users will only tend to have traffic flow and average speed information, and relationships between these parameters and those describing cycle dynamics on urban roads are not well-established. As a consequence, cycle dynamics has not usually been taken into account quantitatively.

(ii) Several studies have concluded that emissions should be described in terms of engine speed, load, power, and the changes in these parameters, not just variables relating to vehicle speed (Leung and Williams, 2000; Kean et al., 2003).

Nevertheless, the concept is a useful one, especially when there is a need to discuss more advanced forms of modelling than the average-speed approach.

\(^{7}\) In this Report the term ‘vehicle operation’ refers to a wide range of parameters which describe the way in which a driver controls a vehicle (\(e.g.\) average speed, maximum speed, acceleration pattern, gear-change pattern), as well as the way in which the vehicle responds (\(e.g.\) engine speed, engine load).

\(^{8}\) In this context, the term ‘transient’ refers to a driving cycle in which the operation of the vehicle is continuously varying, as opposed to being in a steady-state.
1.2.3 ‘Corrected’ average speed models

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

1.2.4 Traffic situation models

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

The user must be able to relate to the way in which the traffic situations are defined in the model. For example, the Handbook of Emission Factors (HBEFA), used in Germany, Austria and Switzerland, is based on reference emission factors for different categories of vehicle. Each emission factor is associated with a particular traffic situation, characterised by the features of the section of road concerned (e.g. ‘motorway with 120 km h\(^{-1}\) limit’, ‘main road outside built-up area’). The speed variation (dynamics) variable is not quantified by the user, but is defined by a textual description (e.g. ‘free-flow’, ‘stop and go’) of the type of traffic situation to which an emission factor is applicable (INFRAS, 2004). As with any other model, the emission factors produced by the Handbook for the various vehicle categories must then be weighted according to traffic flow and composition.

However, asking the user to define the traffic situation using a textual description of speed variation or dynamics may lead to inconsistencies in interpretation. Even qualitative descriptions, such as those employed in the HBEFA, may be beyond many users, and are obviously open to interpretation. Furthermore, there are no universally accepted definitions for traffic situations, and there are likely be significant differences between the absolute characteristics of traffic in different cities. In addition, the Handbook employs definitions which are road- or traffic-based, rather than emissions-based. Although it is known that there are fundamental underlying relationships between the characteristics of the road (e.g. number of lanes, carriageway width, topography), the prevailing traffic (e.g. flow, composition) and the operation of vehicles, relationships with vehicle emissions are less well known.

1.2.5 Multiple linear regression models

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

In modal models emission factors are allocated to the specific modes of vehicle operation encountered during a trip. Different types of modal model are in use, and the terminology used can be rather confusing. In the simpler type of modal model, vehicle operation is defined in terms of a relatively small number of modes—typically idle, acceleration, deceleration and cruise. This type of model is indeed normally referred to as ‘modal’. A number of more detailed modal models aim to provide a more precise description of vehicle emission behaviour by relating emission rates to vehicle operation during a series of short time steps (often one second). These detailed modal models are the subject of this Report, and indeed the project as a whole. However, several different terms (as well as modal) have been used to describe the more detailed type of model, including ‘instantaneous’, ‘microscale’, ‘continuous’ and ‘on-line’ (De Haan and Keller, 2000). As the term ‘instantaneous’ has been used quite widely in the literature, it will be retained for this Report, and will be used hereafter. In fact, such models tend to be discrete in nature, and therefore the term ‘instantaneous’ is something of a misnomer, but this will have to be overlooked.

‘Simple’ modal models

As mentioned above, simple modal models categorise vehicle operation according to a relatively small number of modes. For each of the modes the emission rate for a given vehicle category and pollutant is assumed to be fixed, and the total emission during a trip, or on a section of road, is calculated by weighting each modal emission rate by the time spent in the mode. For example, the Urban Road Pollution (UROPOL) model (Hassounah and Miller, 1995) combines the numbers of vehicles that are accelerating, decelerating, queuing or cruising at any point along a road segment, with emission rates relating to each driving mode. The coarse model approach has usually been used to determine the impacts of traffic control measures and signal improvements (e.g. Coelho et al., 2005). A similar approach been used by, for example, Frey et al. (2001), Rouphail et al. (2001), Unal et al. (2003) and Hung et al. (2005).

Instantaneous models

Atjay and Weilenmann (2004) stated that the aim of instantaneous emission modelling is to map emission measurements from tests on a chassis dynamometer or an engine test bed in a neutral way. In theory, the advantages of instantaneous models include the following:

- Emissions can be calculated for any vehicle operation profile specified by the model user, and thus new emission factors can be generated without the need for further testing.
- The models inherently take into account the dynamics of driving cycles, and can therefore be used to explain some of the variability in emissions associated with given average speeds.
- The models allow emissions to be resolved spatially, and thus have the potential to lead to improvements in the prediction of air pollution.

Some instantaneous models, especially the older ones, relate fuel consumption and/or emissions to vehicle speed and acceleration during a driving cycle, typically at one-second intervals. Other models use some description of the engine power requirement. However, it must be noted that there are a number of fundamental problems associated with instantaneous models. For example, it is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and then it is not straightforward to allocate those emission values to the correct operating conditions. Atjay and Weilenmann (2004) noted that, during measurement in the laboratory, an emission signal is dynamically delayed and smoothed, and this makes it difficult to align the emissions signal with the vehicle operating conditions. Such distortions have not been fully taken into account in instantaneous models until relatively recently.

Some consideration also ought to be given to the model user. In order to apply instantaneous models detailed and precise measurements of vehicle operation and location are required, otherwise any potential benefits may be lost. This is likely to be rather difficult for many model users, as such information is relatively expensive to collect. As a consequence, the use of instantaneous models has mainly been restricted to the research community.
1.3 Report structure

The subsequent Chapters of this report are separated broadly according to the types of instantaneous model described above. There appears to be no accepted term or simple phrase in the literature which adequately describes the difference between models in which the distortion of the emission signals is taken into account, and models in which it is not. The words ‘dynamic’ and ‘static’ have been employed in this sense by some authors (e.g. Atjay and Weilenmann, 2004). However, as similar terms are used to describe the properties of driving cycles, they are probably best avoided here. For the purposes of this report, the term ‘unadjusted’ is used to refer to models in which the distortion is not addressed. Conversely, the term ‘adjusted’ is used to describe models which do address the distortion. These terms are not entirely satisfactory, but should not lead to confusion in the current context.

Chapter 2 describes unadjusted models in which the mapping of emissions is performed by relating the emission signals to causative variables such as speed, acceleration. Chapter 3 describes unadjusted models in which the mapping of emissions is performed by relating the emission signals to engine power. The potential limitations of unadjusted models, and the development of adjusted models, are discussed in Chapter 4. Principles are explained by reference to specific models. For each model identified, the review includes an overview, a description of the modelling approach and a brief description of the software. Important aspects of the model development process are validation, the assessment of model uncertainty, and the assessment of model sensitivity, and any activities in relation to these aspects are also discussed. Chapter 5 provides a summary of the models included in the review, including basic details relating to the supplier, cost, and capabilities.
2 ‘Unadjusted’ models based on speed and acceleration

In the simplest type of instantaneous emission model, emissions and fuel consumption rates are defined for different combinations of instantaneous speed and acceleration, usually in a matrix of bin ranges. For each combination of speed and acceleration the emission or fuel consumption rates are usually based upon the average results from the tests on number of vehicles over different driving cycles. Examples of this approach can be found in Pischinger and Haghofner (1984), Sorensen and Schramm (1992) and Hansen et al. (1995). Other researchers have used the product of speed and acceleration instead of the acceleration rate alone (e.g. Jost et al., 1992; Hassel et al., 1994; BUWAL, 1994; Joumard et al., 1995).

Some of the first examples of European instantaneous models were DGV (Digitised Graz model) (Sturm et al., 1994) and MODEM (Jost et al., 1992; Joumard et al., 1995). These models, which are described in the following Sections, were very similar in their method of operation, although MODEM is the more comprehensively documented in English.

2.1 MODEM

2.1.1 Background

The original version of MODEM was produced during the European Commission’s DRIVE programme. Laboratory emission test data collected by various European laboratories formed the basis of the model. Through the statistical analysis of a large-scale survey of vehicle operating characteristics in urban areas, INRETS developed a set of 14 driving cycles to be repeated on a chassis dynamometer (André et al., 1991). Using these cycles, emission measurements were obtained for a sample of 150 cars of different types. The gear-shift points for each vehicle were calculated with respect to the specific gear and axle ratios, rated power, and maximum engine speed. During each laboratory emission test, hot exhaust emissions of CO, CO\textsubscript{2}, HC and NO\textsubscript{x} were measured on a second-by-second basis, with fuel consumption being determined by carbon balance. The pollutants were measured using conventional laboratory analysers, and vehicle speed was recorded with sufficient precision to allow accelerations to be calculated (Jost et al., 1992).

The first version of MODEM was designed for urban traffic conditions, and could only deal with vehicle speeds up to 90 km h\textsuperscript{-1}. An additional set of emissions factors for use in MODEM was developed later by TRL to allow the model to be used for higher speeds. A further shortcoming of the original MODEM model was the coarse resolution of the speed and acceleration bands. Consequently, a matrix with a finer resolution was also developed for the extended version of MODEM (Barlow, 1997).

2.1.2 Modelling approach

Original version

MODEM was based on the principle that the engine power determines the rate of emission, and the power required depends upon the speed and the rate of acceleration. However, for a given engine power output, a slow moving vehicle will accelerate at a considerably higher rate than a fast moving vehicle. From the analysis of emission data, the best indicators of the power demand were found to be vehicle speed and the product of the vehicle speed and acceleration (Figure 2) (Jost et al., 1992; Joumard et al., 1995). The emission functions for a particular vehicle category and pollutant were therefore defined in the form a two-dimensional matrix, with the columns representing speed intervals (km h\textsuperscript{-1}), and the rows representing the speed x acceleration intervals (m\textsuperscript{2} s\textsuperscript{-3}). For a particular test vehicle the emission rate recorded during each second of a test was entered into the cell of the matrix which corresponded to the speed and acceleration at the time of the measurement. The final emission factor in a given cell was calculated as the arithmetic mean of all the values entered in that cell (averaged over all cycles and appropriate vehicles). The CO emission matrix corresponding to Figure 2 is shown in Table 3. The speed range defined in MODEM was 0 km h\textsuperscript{-1} to 90 km h\textsuperscript{-1}, in increments of 10 km h\textsuperscript{-1}. The speed x acceleration values ranged from -15 m\textsuperscript{2} s\textsuperscript{-3} to +15 m\textsuperscript{2} s\textsuperscript{-3}, in increments of 5 m\textsuperscript{2} s\textsuperscript{-3}.
A review of instantaneous emission models for road vehicles

Figure 2: CO emissions per hour as a function of instantaneous speed and acceleration for petrol catalyst cars with an engine size between 1.4 and 2.0 litres (Jost et al., 1992).

Table 3: MODEM emission factor matrix - CO emissions (g h⁻¹) from petrol catalyst cars (1.4-2.0 litres) as a function of instantaneous speed and acceleration (Jost et al., 1992).

<table>
<thead>
<tr>
<th>Speed x acceleration (m²s⁻³)</th>
<th>Speed (km h⁻¹)</th>
<th>0</th>
<th>5</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
<th>55</th>
<th>65</th>
<th>75</th>
<th>85</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15</td>
<td></td>
<td>-</td>
<td>-</td>
<td>66</td>
<td>56</td>
<td>63</td>
<td>69</td>
<td>59</td>
<td>76</td>
<td>92</td>
<td>115</td>
</tr>
<tr>
<td>-10</td>
<td></td>
<td>-</td>
<td>-</td>
<td>57</td>
<td>61</td>
<td>63</td>
<td>84</td>
<td>94</td>
<td>141</td>
<td>129</td>
<td>134</td>
</tr>
<tr>
<td>-5</td>
<td></td>
<td>-</td>
<td>53</td>
<td>53</td>
<td>73</td>
<td>85</td>
<td>102</td>
<td>130</td>
<td>204</td>
<td>194</td>
<td>325</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>33</td>
<td>59</td>
<td>74</td>
<td>116</td>
<td>123</td>
<td>131</td>
<td>196</td>
<td>193</td>
<td>274</td>
<td>152</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>-</td>
<td>142</td>
<td>163</td>
<td>192</td>
<td>192</td>
<td>207</td>
<td>275</td>
<td>263</td>
<td>350</td>
<td>211</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>-</td>
<td>274</td>
<td>301</td>
<td>295</td>
<td>357</td>
<td>330</td>
<td>454</td>
<td>403</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>-</td>
<td>-</td>
<td>469</td>
<td>568</td>
<td>603</td>
<td>779</td>
<td>706</td>
<td>1041</td>
<td>308</td>
<td></td>
</tr>
</tbody>
</table>

In the model different types of car are defined according to ‘layers’. These layers, which represent given combinations of engine type, technology level, and engine size, are listed in Table 4. Petrol non-catalyst cars were divided into two groups according to compliance with different emission control legislation ¹⁰. The most recent legislative class of vehicles included in MODEM is Euro I. Given that the newest petrol and diesel vehicles on the road conform to Euro IV standards, the model is now somewhat out of date.

For each layer, the original MODEM model estimates fuel consumption and hot exhaust emissions of CO, HC, NOₓ, and CO₂ on a second-by-second basis. The user must enter a driving pattern which defines vehicle speed as a function of time. From the input driving pattern the MODEM program evaluates the average speed and acceleration between each pair of adjacent speed readings, and the corresponding emission factor is then referenced for each vehicle category. Emissions over the entire driving pattern are calculated as the sum of the individual emission factors. Occasionally, operating conditions will be encountered which are outside the speed-acceleration envelope of the model. In such cases, the model defaults to the nearest emission value (i.e. the highest or lowest) on the speed or speed x acceleration axis.

¹⁰ ECE 15.03 (EC directive 78/665/EEC) and ECE 15.04 (EC directive 83/351/EEC).
Table 4: Car category layers used in the MODEM model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Engine type</th>
<th>Technology</th>
<th>Engine Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Non-catalyst ECE 15.03</td>
<td>&lt;1.41</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>ECE 15.04</td>
<td>1.4 - 2.01</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>&gt; 2.01</td>
</tr>
<tr>
<td>4</td>
<td>Petrol</td>
<td>Non-catalyst ECE 15.03</td>
<td>&lt;1.41</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>ECE 15.04</td>
<td>1.4 - 2.01</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>&gt; 2.01</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Catalyst (Euro I)</td>
<td>&lt;1.41</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>1.4 - 2.01</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>&gt; 2.01</td>
</tr>
<tr>
<td>10a</td>
<td>Diesel</td>
<td></td>
<td>&lt;1.41</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Euro I</td>
<td>1.4 - 2.01</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>&gt; 2.01</td>
</tr>
</tbody>
</table>

*a As the majority of diesel cars have engine sizes >1400cc, the emission factors for layer 10 are assumed to be identical to those for layer 11.

Extended version

The first version of MODEM was designed for urban traffic conditions, and could only deal with vehicle speeds up to 90 km h⁻¹. An additional set of emissions factors for use in MODEM was developed by TRL to allow the model to be used for higher speeds. As few emissions measurements were available for high-speed driving conditions, a further series of tests was commissioned by the Highways Agency. Thirty-seven vehicles were included in the test programme. In addition to the gaseous pollutants mentioned above, emissions of particulate matter from diesel vehicles were measured both by collection on a filter over the total duration of each test cycle, and on a second-by-second basis using a TEOM (Tapered Element Oscillating Microbalance) (Barlow, 1997).

A further shortcoming of the original MODEM model was the coarse resolution of the speed and speed x acceleration bands. The emission factor matrices were originally divided into only 10 speed bands and 7 speed x acceleration bands (Table 3). This resulted in step changes in emission estimates as the vehicle operation changed from one band to the next. On long trips, the overall effect of these step changes was minimal. However, for short trips where small changes in the vehicle speed occurred, the effect could be substantial. Consequently, a matrix with a finer resolution was developed for the extended version of MODEM (Barlow, 1997).

Theoretically, the finer the resolution of the emission factor matrix, the higher the model accuracy. However, as the resolution improves the complexity of the calculations increases. Furthermore, as the speed and acceleration band sizes decrease the number of occurrences within a particular matrix cell also decreases. Various matrix sizes were tested, and a compromise was reached which resulted in a sufficiently detailed grid with sufficient occurrences in the majority of cells. The speed bands in the extended model ranged from 0 km h⁻¹ to 147 km h⁻¹, with a band width of 6 km h⁻¹ (i.e. each band covered ±3 km h⁻¹ of its nominal value). This equated to a total of 26 speed bands. The speed x acceleration bands ranged from -40 m² s⁻³ to +30 m² s⁻³, with a band width of 2 m² s⁻³. This equated to 36 speed x acceleration bands in total. Most of the distribution lay within the low values of speed x acceleration, and therefore covered typical driving (i.e. driving with moderate accelerations and decelerations). At higher values of speed x acceleration the number of occurrences was lower, with some cells having no values at all. However, these extreme points are only occasionally required in emissions estimates. In order to fill empty cells each distribution was extended, based on the values of neighbouring cells, and a smoothing function was used to remove excessive peaks and troughs. To provide an even finer resolution, an interpolation scheme was applied to the points between the known values. This resulted in bands of 11 km h⁻¹ for speed and 1 m² s⁻³ for speed x acceleration (Barlow, 1997).

There are limitations on the speeds and accelerations that can be driven on a chassis dynamometer, and therefore it was not possible to test every combination of speed and acceleration which can be achieved using a high-powered car. However, the test cycles used for this work covered most of the speed and accelerations.
that are encountered during normal driving.

2.1.3 Validation

An attempt to validate the original MODEM model by comparison with measured emissions over a given driving pattern gave poor results, probably due to only two vehicles being tested (Joumard et al., 1995). Because of the large variability in emissions from individual vehicles, the model cannot accurately predict emissions on this level. However, Joumard et al. (1995) argued that the model should be able to produce a good estimate of the emissions for a typical traffic stream based on the instantaneous operating parameters of the vehicles.

In the case of the extended model, the use of the derived factors to estimate the emissions over the test cycles showed that, although there was some noticeable differences from estimates using the MODEM model, the agreement with the actual measured values was very good. The comparison between the estimated PM emissions using the derived emission factors and the average actual results was not as good. Therefore, although the emissions factors can be used to give an idea of the particulate emissions, these should be viewed with caution.

2.1.4 Software description

The original version of MODEM was written in the C programming language and runs in DOS. The program is extremely easy to use, with the only requirements being that the user specifies the driving pattern in the correct format, and identifies different directories for the input and output data. Figure 3 shows the MODEM output summary screen. A separate file, which gives the emissions produced during each second of the driving pattern, is also produced. The model is commercially available, with a price of £1,000 for research purposes and £6,000 for commercial purposes. The price was set by the project consortium at the time of its release (more than 10 years ago).

![Figure 3: Original MODEM user interface (output sheet).](image-url)
2.2 Digitised Graz Model

2.2.1 Background

One of the first instantaneous models was the Digitised Graz Model, DGV. The model was developed by the Institute of Combustion Engines and Thermodynamics of the Graz University of Technology in Austria, and is not widely known in the UK.

2.2.2 Modelling approach

In principle and operation, the DGV model is very similar to the MODEM model. The model calculates hot exhaust emissions of passenger cars with the aid of emission maps expressed in terms of the vehicle speed and acceleration. Three base emission maps were developed: one for non-catalyst (ECE 15/04) cars, one for petrol catalyst cars, and one for diesel cars (model years 1987-88). Using these base maps and a given fleet composition, the model constructs an ‘average’ emission map and then calculates CO, HC, NO\textsubscript{x}, PM emissions and fuel composition from the driving pattern defined by the user. The data in the model were derived from a series of emission tests on a chassis dynamometer using special driving cycles to cover all the cells in the emission matrices. However, tests on only 12 cars were included. Cold-start emission data were provided independently (Pischinger and Haghofer, 1984, Sturm \textit{et al.}, 1994; Sturm, 1996).

2.2.3 Validation

The DGV model has been used to evaluate traffic calming measures in Graz (Sturm \textit{et al.}, 1994), but there appears to have been little reporting in English of validation exercises.

2.2.4 Software description

Again, there appears to be little documentation in English which relates to the DGV software. As it is unlikely that the model is still in use, it is given no further consideration in this Report.
3 ‘Unadjusted’ models based on engine power demand

According to Barth et al. (2001), one problem associated with the speed-acceleration matrix approach is that models are typically based on steady-state emissions, and ignore transient operation. With modern engines and emission control systems there are various ways in which transient effects can occur. Variations in engine load and engine speed require very high flexibility in the control of the fuelling system. In the particular case of spark ignition engines with a three-way catalyst, any transient movement away from stoichiometric fuelling produces a greatly magnified effect at the catalyst exit. Other controls, like EGR\(^{11}\) valves or turbochargers, and their transient behaviour, can also have an important impact on emissions. It is also important to consider temperature effects in engines and catalysts when changing the load conditions of the engine (Pelkmans et al., 2004).

Furthermore, errors are generated by either averaging emission rates within each bin in the matrix, or interpolating between bins. The errors associated with a single bin could accumulate into major computing errors in the final results. Barth et al. (2001) argue that the key to eliminating this kind of error is to establish a correct analytical formula for the important variables.

Another instantaneous modelling approach, and one which appears to be more useful, involves the development of emissions and fuel consumption maps which relate to engine power. Early examples of this approach can be found in Post et al. (1984) and Alcelik (1989). By basing emissions on engine power the effects of, for example, gradient and the use of auxiliaries, as well as speed and acceleration, can be taken directly into account. The engine power is usually derived from a combination of vehicle-specific parameters and the driving pattern specified by the model user. Some examples of specific models are given in the following Sections.

3.1 PHEM (HDV part)

3.1.1 Background

The ARTEMIS project and the COST Action 346\(^{12}\) provided a great deal of insight into the emission behaviour of modern vehicles. One of the main aims of ARTEMIS and the COST Action was to develop a model capable of accurately simulating emission factors for all types of HDV over any driving pattern and for various vehicle loads and gradients; the latter greatly influence driving behaviour and emission levels. The resulting tool - PHEM (Passenger car and Heavy-duty Emission Model) - estimates fuel consumption and emissions based on the instantaneous engine power demand and engine speed during a driving pattern specified by the user (Rexeis et al., 2005).

The HDV part of PHEM does not include adjustments for the distortion of the emissions signal during measurement. The measurement programme and the development of the modelling approach are well documented in English, and are described in more detail below. The passenger car part of the model, on the other hand, does include a signal adjustment, and is therefore described later in the Report.

3.1.2 Modelling approach

Overview

The methodology for PHEM was selected following an extensive literature review and feasibility study by Hausberger (1998). The review noted that most HDV models have employed a similar methodology – based on engine power demand and speed - to simulate emissions, and this general approach was also adopted for PHEM. Figure 4 shows the structure of the model. The main inputs are a user-defined driving pattern and a file describing vehicle characteristics. For every second of the driving pattern PHEM calculates the actual engine power demand based upon vehicle driving resistances and transmission losses, and calculates the actual
engine speed based upon transmission ratios and a gear-shift model. The engine power and speed are then used
to reference the appropriate emission (and fuel consumption) values from steady-state engine maps. The
emission behaviour over transient driving patterns is then taken into consideration by ‘transient correction
functions’ which adjust the second-by-second steady-state emission values according to parameters describing
the dynamics of the driving pattern.

Figure 4: Structure of PHEM (Rexeis et al., 2005).

The HDV part of PHEM is optimised for simulating fuel consumption and emissions from HDV fleets, but can
also be used for simulations of single vehicles. The outputs from the model are engine power, engine speed,
fuel consumption and emissions of CO, CO₂, HC, NOₓ and PM every second, as well as average values for the
entire driving pattern.

Steady-state measurements

Steady-state measurements on 102 engines were used to develop PHEM. Figure 5 shows the measurement
points used in the ARTEMIS test programme. The steady-state tests included the operating conditions in the
regulatory ECE-R49" and ESC tests. However, for the development of real-world emission factors for
modern engines it is essential to incorporate ‘off-cycle’ measurements. As electronic engine control systems
(used for Euro II onwards) allow different injection timing, the optimisation of fuel consumption can result in
increased emissions outside the regulation test points. Emission maps based solely on the regulatory tests
would significantly underestimate emission levels for many engines, especially for NOₓ. The common-rail
injection systems used in Euro III engines give additional degrees of freedom, such as the possibility for pre-
and post-injection" and offer the possibility of altering PM emissions within the engine map. Consequently,
29 additional points were included to cover off-cycle emissions. Wherever possible, a PM emission map was
measured. As each point had to be run for a rather long time to collect enough PM on the filter, this was not
possible for all engines and test points (Rexeis et al., 2005).

Figure 6 shows typical NOₓ emission maps for Euro I, Euro II and Euro III engines. The emission maps are
normalised for engine speed and engine power, and the emission values are given in g kW⁻¹ h⁻¹ rated power.
This unit is used in the model, and allows engines with different rated power to be compared directly.

13 The ECE-R49 is a 13-mode steady-state test cycle, introduced by ECE Regulation No.49 and then adopted by the EEC Directive
88/77, and was used for type approval up to and including Euro 2 level.
14 The ESC (European Stationary Cycle) was introduced for emission certification of Euro III heavy-duty engines in October 2000.
15 Computer-controlled fuel injectors can ‘shape’ the fuel injection curve using multiple injection events. A small amount of fuel can
be pre-injected early in the compression cycle to begin the burning process. This eliminates much of the engine noise previously
associated with diesel engines. This is followed by the main fuel injection pulse. The timing and delivery of the main pulse also
controls combustion noise and emissions. Lastly, a post-injection pulse can help to burn off soot produced during the main burn.
A review of instantaneous emission models for road vehicles

Figure 5: Steady-state points measured in the ARTEMIS programme.
(example full-load curve).

Figure 6: Typical steady-state NOx emission maps for Euro I, Euro II and Euro III engines (Rexeis et al., 2005).

Transient measurements

A detailed description of the transient test programme is given by Hausberger (2001). For 27 engines both transient tests and complete steady-state emission maps were available. Several different driving cycles were used, with the cycles being designed to cover different transient engine load patterns. The data from the transient measurements were used mainly for the assessment of the effects of transient operation on emission behaviour, compared with steady-state conditions. When steady-state emission maps are used to calculate ‘quasi-steady-state’ emissions for transient cycles, large differences are observed between the calculated and measured emissions, especially for CO, HC and PM. It is assumed that the differences are a result of changes in combustion conditions (e.g. inlet pressure and temperatures). Calculations based only on interpolation from the steady-state engine maps resulted in the underestimation of PM emissions over transient cycles by up to 50%. In general, however, Euro III engines were less sensitive to transient conditions than Euro I and Euro II engines. This suggests a better application of these engines to changing conditions under transient load.
Engine power and engine speed simulation

For a correct simulation of engine power, all driving resistances occurring during real-world operation have to be taken into consideration. The actual engine power ($P$) is calculated according to the equation:

$$P = P_{\text{rolling resistance}} + P_{\text{air resistance}} + P_{\text{acceleration}} + P_{\text{gradient}} + P_{\text{transmission losses}} + P_{\text{auxiliaries}} \quad \text{Equation 1}$$

The individual terms in the total power demand equation are calculated as described by Rexeis et al. (2005). The actual engine speed is calculated using the vehicle speed, the wheel diameter and the transmission ratios. A given vehicle speed can be achieved in any one of a number of different gears, and actual gear selection depends on a subjective assessment by the driver. Gear-shift behaviour is modelled in PHEM for three different types of driver: (i) ‘fast’, (ii) ‘economical’ and (iii) ‘average’. For these driving styles, engine speed limits are defined to determine when the gear has to be changed upwards or downwards. Many checks and additional gear-shift rules are necessary to avoid erratic gear-shift behaviour in the model.

Normalisation of steady-state engine emission maps

A significant problem when modelling HDV emissions is having a sufficient number of measured engines in each fleet segment, since more than 100 segments of the fleet have to be covered. Since each size class has typical values for rated engine power, each measured engine can be applied to only one fleet segment. To avoid a separation of the measured engines according to the rated engine power, the engine maps were normalised and brought into a standard format (a 40-point map). This enabled the development of average engine maps which were independent of engine size, and guaranteed that the single HDV fleet segments were covered by a proper number of measurements on different engines (Rexeis et al., 2005).

Transient correction functions

The emission rate of a pollutant can also be strongly dependent on the rate of change of engine load. As stated earlier, these transient effects must be taken into account in models. The main problem in the development of dynamic correction functions is the identification of parameters which express the dynamic aspects of a driving cycle and also correlate well with the difference between measured emissions and the ‘quasi-steady-state’ emissions calculated for the transient cycle. For each engine, multiple regression analysis was used to determine relationships to describe the differences between the measured emissions over the transient cycles and the emissions calculated using the normalised steady-state engine maps. The parameters giving similar equations for all engines were then filtered out, and using this set of equations the accuracy of the simulation was improved for all engines over almost all cycles.

Figure 7 shows the results obtained using the transient correction function for eight Euro II engines and three Euro III engines. For each of these engines between three and five transient cycles were measured. Whilst PM emissions were underestimated when simply interpolated from the steady-state engine maps, the use of the transient correction resulted in predicted emission levels which were closer to the measured values. For CO and HC similar results were achieved. For NOx emissions the transient influences were small, and the transient correction function gave only slight improvements. As the influence of transient effects on the overall emission level for the emission standards from Euro IV onwards was assumed to be small, the corresponding transient correction functions were set to zero. For PM, the low emission limits would not allow a significant increase under transient conditions compared with steady-state conditions. Even if the transient PM emissions in the raw exhaust gas increased, the effect would probably be reduced by the exhaust gas after-treatment system.
Estimation of emissions from Euro IV and Euro V vehicles

The Euro IV standards came into force in October 2005 for the type approval of new engine models. For Euro V the corresponding implementation date is October 2008. In PHEM the assessment of the emission behaviour of engines meeting these standards is highly uncertain, as no production vehicles were available for measurement. Furthermore, the effects of the new technologies used to meet the type approval limits are difficult to predict. It was concluded from the measurement programme on Euro II and Euro III engines that simply extrapolating emission factors from older engine technologies to future standards according to the future emission limits is not a suitable approach.

In general, three approaches for meeting the Euro IV and Euro V type approval limits will be available in the near future: improved engine technology, exhaust gas after treatment and alternative combustion concepts. Whilst compliance with the Euro IV limits could be achieved with improved conventional engine technologies (fuel injection, exhaust gas recirculation, variable turbine geometry at the turbo charger, etc.), this is rather unlikely for Euro V (Rexeis et al., 2005).

Various filter-based after-treatment systems are currently being developed to reduce PM emissions from HDVs – these are collectively known as diesel particulate filters (DPFs). Systems include continuously-regenerating traps, fuel-borne catalyzed filters and diesel particulate catalysts. There are two main approaches for reducing NOx emissions: selective catalytic reduction (SCR), and exhaust gas re-circulation (EGR). These systems are described in more detail by Rexeis et al. (2005). The main issue in relation to the emission maps for Euro IV and Euro V engines is whether such technologies have a varying efficiency over a map.

High fuel efficiency is the main aim for HDV engine manufacturers, and is crucial for competitiveness in the sector. For Euro IV and Euro V vehicles, it must also be assumed that manufacturers will continue to focus on fuel efficiency for low investment and running costs. In PHEM, it is assumed for the development of the basic emission maps that DPFs would not be widely used in Euro IV and Euro V engines. The option of ‘DPF-technology’ can be chosen, which assumes a reduction in PM mass of approximately 90%, and an increase in fuel consumption of 3%, compared with the relevant basic engine emission map. This option may be helpful for assessing measures such as the introduction of DPFs in urban bus fleets.

For NOx emissions, the basic technology for compliance with the Euro IV limits will be SCR. This slightly increases the fuel consumption factors for this fleet segment. All Euro V HDVs will use SCR technology. The application of SCR will be optimised in the regions of the engine map covered by the type approval tests. OBD systems will also be installed, limiting NOx emissions everywhere on the engine map to 5 g/kWh for Euro IV and to 3.5 g/kWh for Euro V. The application of SCR allows for higher raw exhaust NOx emissions. This enables further optimisation of fuel consumption (earlier injection timing). Compared with Euro III engines, reductions of around 7% for Euro IV and 5% for Euro V are predicted (Rexeis et al., 2005).
3.1.3 Validation

Laboratory validation

In order to simulate the fuel consumption and emissions of the individual HDVs measured on the chassis dynamometer, all relevant parameters in the PHEM input data files were set either to the manufacturers’ specifications or to measured values. Rolling resistance coefficients and drag coefficients were obtained from coast-down tests on the road, and the 40-point standardised engine emission map, the full-load curve, the average transient correction function and the gear-shift model settings were obtained for the actual vehicle or for the corresponding vehicle category. For single vehicles, NO\textsubscript{x} emissions were estimated to within +/-25% of the measured values. The deviation for HC and PM was between around -30% and +50%. The results for CO emissions from a single HDV were relatively poor (-40% to +100% deviation).

Real-world validation

The real-world validation of PHEM was conducted using both on-road emission measurements (validation of the simulation results for single vehicles) and tunnel measurements (validation of the results for the emission level of the vehicle fleet).

An articulated HGV with a kerb mass of 40 tonnes was used in an on-road measurement campaign, which was performed by EMPA in Switzerland. The concentrations of pollutants, mass flows, pressures, temperatures, engine speed and torque were measured. After the on-road measurements, the engine was removed from the vehicle and operated on an engine test bed over several cycles. The laboratory and on-road measurement equipment were operated in parallel. For the PHEM prediction the vehicle category ‘tractor-semitrailer 34 to 40 tonnes maximum allowed gross weight’ was used. Only vehicle-specific data were replaced by the values for the test vehicle. These included the engine emission maps with transient correction functions (obtained from the engine test bed measurements), the transmission ratios of the gearbox, and the total vehicle mass. The measured on-road vehicle speed and road gradient were used as model inputs. The simulation of the required engine power based on the vehicle specifications and the trip data (vehicle speed and road gradient) matched the measured values almost exactly. The measured and simulated fuel consumption agreed to within ±2%. NO\textsubscript{x} emissions were underestimated by the model by between 0% and 4%. The predicted THC and CO emissions differed from the measured values by -3% to -15% (Rexeis et al., 2005).

The PHEM predictions for real-world traffic situations were also compared with emission factors derived from measurements in the Plabutschtunnel in Graz, Austria. Standard air quality monitoring equipment was installed in a lay-by within the tunnel, and the emission factors for light-duty vehicles and heavy-duty vehicles were calculated using information on traffic flow and air flow speed in the tunnel. The driving cycles recorded in the Plabutschtunnel were used as input to PHEM. The results of this simulation agreed closely with the emission factors obtained from the road tunnel measurements.

3.1.4 Software description

The model takes the form of a computer-executable program with a user-friendly interface (Figure 8). This user interface allows the user to open vehicle and driving cycle files, to edit the file content, and to set the options for the calculations to be performed.

The input files for PHEM are modular to allow easy editing. The basic files needed are:

* .gen This file saves the settings and the sub files selected.
* .veh Vehicle file - contains the relevant information on the vehicle and the engine.
* .map Contains the engine emission map.
* .dri/*.npi Contains the driving cycle for either the vehicle (*.dri) or the engine (*.npi).
* .fld Full-load curve for the engine.

In order to allow transient correction functions to be applied, the following file is also needed:

* .trs Contains the transient parameters.
PHEM allows the following calculations to be made:

**Total vehicle:** PHEM simulates the engine power and the engine speed from the vehicle driving pattern and gives the fuel consumption and the emissions.

**Engine only:** Simulates the emissions for an engine cycle (e.g. for comparison with measurements on the engine test bed). Requires the engine power, idling speed, rated engine speed and inertial mass.

**Emission map:** Creates an engine emission map from measurements on the chassis dynamometer.

**Engine analysis:** This offers an automatic comparison of measured and simulated emission values for engine tests. The transient correction parameters are also plotted.

**Standard map:** Creates emission maps with a standardised location of the points in the map from the measured steady-state tests used as input.

TUG have provided a provisional indication of the cost of PHEM. There is a split pricing structure, with participants in ARTEMIS and COST 346 being offered preferential rates. For these participants the source code is provided free of charge. The HDV input data (average engine maps, vehicle files, etc.) are available for Euro 3,000 €, and the input data for passenger cars for 4,000 €. For non-participants, the proposed costs of the source code, HDV input data and passenger car input data are 5,000 €, 7,000 € and 6,000 €. The price for the full model includes 20 hours of consultancy. If the PHEM source code is purchased, 8 hours training and a user manual are included.
3.2 VeTESS

3.2.1 Background

An emissions model called VeTESS (Vehicle Transient Emissions Simulation Software) was the main Deliverable from the European Commission 5th Framework DECADE project. The project was led by MIRA, with principal contractors including IDIADA Automotive Technology, the Centre of Logistics and Expert Systems GmbH (CLE), and Vlaamse Instelling voor Technologisch Onderzoek NV (VITO). One aim of DECADE, as with PHEM, was to further develop quasi-steady-state modelling methods by taking into account the dynamic behaviour of the engine system.

3.2.2 Modelling approach

VeTESS calculates the emissions from a single vehicle during a driving pattern defined by the model user. The driving pattern contains details of the speed of the vehicle and the road gradient over a route and, when coupled with information on the vehicle, forms the basis of a series of calculations that derive the engine power required at every point on the route (MIRA, 2002).

In a similar way to PHEM, VeTESS determines the engine operating conditions from the forces acting on the vehicle. The total force \( F_{\text{total}} \) on the vehicle is calculated through the equation:

\[
F_{\text{total}} = F_{\text{accel}} + F_{\text{climb}} + F_{\text{roll}} + F_{\text{aero}}
\]

Equation 2

The acceleration resistance \( F_{\text{accel}} \) is the force required in order to cause an acceleration of the mass of the vehicle.

The climbing resistance \( F_{\text{climb}} \) is the component of the weight force of the car acting parallel to the slope. It increases with increasing gradient.

The rolling resistance \( F_{\text{roll}} \) originates from the deformation processes that occur at the contact patch between the tyre and the road. It is affected by tyre characteristics such as diameter, width, aspect ratio, rim width, inflation pressure, tread depth, etc. A vehicle’s rolling resistance is also affected by transmission efficiencies.

The aerodynamic resistance \( F_{\text{aero}} \) is due to the interaction between the vehicle and the air. Aerodynamic resistance is principally due to two interactions:

1. Interaction with the layer of air immediately next to the vehicle (called the boundary layer) which gives rise to skin friction drag.
2. Interactions with the air at greater distances than the boundary layer causing pressure differences around the vehicle that give rise to pressure drag.

Skin friction drag and pressure drag are calculated from the vehicle’s drag coefficient, frontal area, relative speed (relative to ambient wind speed) and air density.

The engine provides the force required to overcome these resistances to motion, and this force is produced by the engine as a torque. This torque is converted from rotational to linear motion by the driven wheels. The drive train contains many components, each of which loses energy through inefficiency. From the force required to move the vehicle, VeTESS can calculate the speed and torque at the wheel, the speed and torque at the prop shaft, and hence the engine speed and torque.

The parameters required to calculate the vehicle’s power requirement are retrieved from vehicle and engine specification files. The vehicle file contains all the information specific to the vehicle being tested which affects the power required during driving. In the vehicle file, rolling resistances are defined via two coefficients used to describe static and dynamic conditions. The engine file contains information describing the engine specifications and fuel details. Emission maps containing specific emission values for varying engine demand conditions are also contained within the engine file.
To describe an engine fully, four emission components are defined in VeTESS (Pelkmans et al., 2004):

- A ‘steady-state’ emission. This describes the rate at which a pollutant is produced as the engine runs under steady speed and torque.
- A ‘jump fraction’ emissions. This describes the fraction by which the emissions rate jumps immediately, following a change in torque, to the value for the new steady-state.
- A ‘time constant’ emission. This describes the time constant with which the emissions rate approaches the steady-state value following a change in torque.
- A ‘transient’ emission. This describes the discreet amount of additional pollutant generated following a change in torque.

For each of the four emission components and each pollutant (CO, HC, NOₓ, CO₂ and PM), emission maps relating to engine speed and torque were derived from test bed experiments on individual engines.

The four components are shown in Figure 9. During transient emissions production there is an initial increase in the emission levels due to the initial change in pedal position. There is a small spike in emissions during the associated change in load. This emission value is often shown as a large peak, but has relatively little effect on emissions production as it acts over a very short time period.

VeTESS calculates the engine speed, engine torque and change in engine torque from the forces on the vehicle, and then references the corresponding values for the four emission components. A time history of the emissions produced over the drive cycle can be produced, and these values can be summed to produce a cumulative figure. The calculation process is summarised below.

During the first step of the calculation VeTESS references the engine’s steady-state emissions map for the value corresponding to the previous emissions rate. It then multiplies this by the time increment.

\[ \text{Area} = E_{\text{prev}} \cdot T_x \]  
Equation 3

---

**Figure 9**: Components of calculation procedure (MIRA, 2002).
Where:

\[ E_{prev} = \text{previous emission rate} \]
\[ T_x = \text{time increment} \]

During the second step of the calculation, VeTESS looks up the emissions value in the jump fraction emissions map. The jump fraction describes the quotient \( a/b \), where \( b \) is the difference between the two steady-state emissions values and \( a \) represents the value of average emissions produced over the previous 15 seconds. This helps the function establish the integration area and represents the fraction by which the emissions rate jumps to the new steady-state value. Both \( a \) and \( b \) are shown in Figure 9.

\[
\text{Area} = \left\{ E_{prev} + \left( \frac{a}{b} \cdot (E_{final} - E_{prev}) \right) \right\} \cdot T_x
\]

Equation 4

Where:

\[ E_{final} = \text{final steady-state output} \]

The third step of the VeTESS emission map look-up procedure uses the time constant to closer approximate the emissions to the new steady-state value. This is achieved via an exponential function:

\[
1 - e^{-\frac{t(x)-15(x)}{\tau_{cT}}}\]

Equation 5

The time constant is defined at the point when the exponential function is best approximated to the measured data. The start value of this function is equal to the jump fraction mean value and the last value is represented by the upper steady-state value.

\[
\text{Area} = \left\{ E_{prev} + \left( \frac{a}{b} \cdot (E_{final} - E_{prev}) \right) \right\} \cdot T_x +
\left\{ \left[ 1 - e^{-\frac{t(x)}{\tau_{cT}}} \right] \cdot (E_{new} - \left( \frac{a}{b} \cdot (E_{new} - E_{prev}) \right) - E_{prev}) \right\} \cdot 0.5 \cdot T_x
\]

Equation 6

Where:

\[ E_{new} = \text{new steady-state output} \]

3.2.3 Validation

Pelkmans et al. (2004) state that a great number of measurements have been used to validate VeTESS, and to quantify the accuracy of the simulation tool both for ‘control’ vehicles (for which transient engine data were measured in depth) and for uncontrolled vehicles (for which transient engine data were not available). The DECADE project initially focused on three vehicles with different engine technologies, representing typical European light-duty vehicles. The selected control vehicles were:

- A Euro IV petrol-engined passenger car (VW Polo 1.4 16V)
- A Euro III medium-large diesel car (Skoda Octavia 1.9TDi, 90).
- A Euro II diesel light commercial vehicle (Citroen Jumper 2.5D).

An extensive series of measurements was performed on the three control vehicles. These included real-world measurements in Mol (Belgium) and Barcelona (Spain) for city, rural and motorway traffic, measurements on a proving ground at IDIADA, and measurements on a chassis dynamometer at CLE, IDIADA and MIRA according to the European certification cycle and a real-world traffic cycle (Mol cycle). Model runs were also conducted for a Van Hool city bus with a Euro II engine, for which sufficiently accurate engine maps were available.

The VeTESS simulations for fuel consumption and CO₂ emissions were generally accurate to within 5% for the three control vehicles. However, deviations in fuel consumption of up to 20% were recorded when there was a mis-matching of the gear-shifting strategy. The results differed between technologies. The best results were obtained for the diesel vehicles, for which the simulation of NOₓ and PM emissions generally has an...
acceptable accuracy (within 10 to 20%). However, specific engine control strategies or single events may have a serious impact on the actual emissions produced on the road. Both light-duty diesel vehicles were equipped with oxidation catalyst, resulting in extremely low CO and HC emissions (<0.05 g km⁻¹). The graph on the left of Figure 10 shows that it was difficult to accurately model emissions (with the exception of CO₂) for the petrol control vehicle (VW Polo). Catalyst behaviour plays an important role, as this can vary depending on engine preconditioning, on external conditions, and on the condition of the catalyst itself. Such factors make it difficult to estimate emissions for modern petrol-engined vehicles equipped with a three-way catalyst, and the effects are difficult to generalise for engine families (Pelkmans et al., 2004).

For heavy-duty diesel engines without exhaust gas after-treatment, simulations based on steady-state engine data gave very acceptable results, especially for fuel consumption, CO₂ and NOx emissions, which are known to be less sensitive to transient effects. The results for CO and HC emissions varied, partly because of the low accuracy of the available engine maps, and partly because of the lack of transient data. The highest accuracy was achieved when the engine data were derived from the actual engine being modelled. This is illustrated in the graph on the right of Figure 10 for the Van Hool city bus (Pelkmans et al., 2004).

The introduction of transient corrections increased the calculated fuel consumption by around 6% for the diesel vehicles, compared with 10% for the petrol vehicle. The introduction of transient corrections increased the calculated PM emissions for the diesel vehicles by around 15%. The transient corrections only had a minor impact on the calculated NOx emissions for the diesel vehicles. The impact of transient corrections on CO and HC emissions was between 20 and 200% for the diesel vehicles (Pelkmans et al., 2004).

Pelkmans et al. (2004) also identified the main limitations of the VeTESS model. The modelling technique considers only one vehicle at a time and one journey at a time. Although the software has been designed to allow the rapid simulation of many vehicles and many journeys, there are more suitable methods (employing emissions factors) for estimating emissions for large fleets and large geographical areas, particularly if precise journey details are not known. The characterisation of a single engine for the VeTESS software can take several weeks. It also involves putting the engine on a test bench in isolation from the vehicle - something that is not possible in many research establishments. Future work will address this problem by examining other ways of gathering the data. In addition, if an engine type or its emission-control equipment is updated, the characterisation must be repeated for the new engine. This means that the simulation technique is not suitable for mass simulation of hundreds of vehicle types. It is more suited to the detailed analysis of a limited number of vehicles and engines. Another pre-requisite of the modelling technique is a detailed description of the journey to be simulated, in terms of vehicle speed and road gradient. For some forms of analysis, such details may not be available. Again, the model is better suited to the analysis of individual cases, whereas emission
factor methods can be used for generic types of journey, area or road.

### 3.2.4 Software description

VeTESS is a windows-based application which is written in the object-orientated programming language Delphi 5, and comprises approximately 4,300 lines of code. The software development process was subject to MIRA’s software control system (MIRA, 2002). Figure 11 shows an example of the VeTESS user interface.

Separate folders are used to hold the data needed by the program to simulate emissions. The folders are ‘vehicles’, ‘engines’, ‘drive cycles’ and ‘results’. VeTESS searches the appropriate folder when opening vehicle files (*.veh), engine files (*.eng) or drive cycle files (*.dcy or *.txt). Results are stored as default in the results folder in text format (*.txt).

![VeTESS User Interface](image)

**Figure 11:** Example of the VeTESS user interface (Pelkmans et al., 2004).

VeTESS also has a ‘drive cycle wizard’, which guides the user through the modelling process. The wizard allows VeTESS to use a wide range of file formats. VeTESS requires, as a minimum, a user-defined driving pattern describing vehicle speed as a function of time. Any time increment can be used, the most common being one second. VeTESS can also use information on road gradient and gear selection if this is available. The majority of the parameters used to determine engine power can also be altered via the interface to allow for user-defined simulations.

VeTESS produces a large range of outputs to aid the analysis of results, including general vehicle information such as the actual speed, the forces acting on the vehicle, and the torque outputs at various parts of the drive train, as well as the emission results. The latter can be displayed in a number of different formats.
3.3 CMEM

3.3.1 Background

In 1995 researchers at the University of California-Riverside, the University of Michigan and Lawrence Berkeley National Laboratory began a four-year project to develop a ‘Comprehensive Modal Emissions Model’ (CMEM), sponsored by the National Cooperative Highway Research Program (NCHRP). The overall objective was to develop and validate an emissions model that accurately reflected light-duty vehicle emissions as a function of vehicle operating mode. The model is capable of predicting second-by-second exhaust (and engine-out) emissions and fuel consumption, and is comprehensive in the sense that it is able to predict emissions for a wide range of vehicle and technology categories, and in various states of condition (e.g. properly functioning, deteriorated, malfunctioning) (Barth et al., 2001).

As the CMEM model has been developed in the United States, it is not wholly appropriate to apply it to the European (and UK) vehicle fleet. Nevertheless, the principles involved in the development of the model are certainly of interest within the context of this Report, and are described in some detail in the following Sections.

In fact, the main purpose of CMEM is to predict vehicle exhaust emissions associated with different modes of vehicle operation such as idle, cruise, acceleration, and deceleration. In this sense CMEM is ostensibly closer to the simpler modal models described in Chapter 2. Nevertheless, the model is rather detailed, takes into account engine power, includes aspects of vehicle operation such as variable starting conditions (cold-start, warm start) and off-cycle driving, and operates on a temporal level which is similar to that of other instantaneous models. It is therefore appropriate to deal with it in this Chapter of the Report.

3.3.2 Modelling approach

Overview

CMEM uses what is termed by Barth et al. (2001) as a ‘physical power-demand’ modal modelling approach based on a ‘parameterised analytical representation of emissions production’. What this means is that the production of emissions is broken down into components which correspond to different physical processes, and each component is then modelled separately using various parameters which are characteristic of the process. These parameters vary according to the vehicle type, engine and emission technology. The majority of the parameters are readily available (e.g. vehicle mass, engine size, aerodynamic drag coefficient), but some key parameters must be deduced from a test programme, although the testing involved is much less extensive than creating emission maps for a wide range of vehicle operating points (Barth et al., 2001).

Using this type of modelling approach, models must be established for the different engine and emission-control technologies in the vehicle fleet. Once these models have been established, it is necessary to identify the key parameters in each component of the models for characterising vehicle operation and emissions production. A critical component of the approach is that emission control malfunction and deterioration are explicitly modelled. The correct modelling of high-emitting vehicles is also an important part of the approach (Barth et al., 2001). In order to predict emission rates, the next step is to combine the models with vehicle operating parameters that are characteristic of real-world driving, including environmental factors such as ambient temperature and air density, as well as dynamic factors such as commanded acceleration, road load, road gradient and the use of auxiliaries (e.g. air conditioning, electric loads). The predicted emission rates can then be compared directly to measured emissions data, and the model parameters or components can be adjusted to establish an optimal fit. This calibration/validation process occurs iteratively until the models are well developed (Barth et al., 2001).

Barth et al. (2001) argue that this type of model is deterministic, in that it based on causal parameters rather than statistical surrogate variables which are not necessarily linked to physical phenomena, and cite several key features which make the modelling approach used in CMEM attractive, including the following:
It inherently handles all the factors which affect emissions, such as vehicle technology, operating modes, maintenance, accessory use, and road gradient.

It is applicable to all vehicle and technology types.

It can be used with both micro-scale and macro-scale vehicle activity characteristics. For example, if a second-by-second driving pattern is given, the model can predict highly-time-resolved emissions. If average vehicle activity characteristics such as average speed, peak average speed and idle time are given, the physical model can still be used based on average power requirements.

It is easily validated and calibrated. Any second-by-second driving pattern can be applied to the model, while simultaneously measuring emissions. Modelled results can be compared with measurements and the parameters of the model can be calibrated accordingly.

It is not restricted to pure steady-state emission events, and emission events that are related to the transient operation of the vehicle are more appropriately modelled.

The model is transparent, and results can be easily dissected for evaluation. It is based on physical science, so that data are tested against physical laws and measurement errors can be identified in the model establishment phase.

There are also some potential disadvantages to such an approach. Establishment of this type of model is data intensive. A large number of physical variables must be collected and/or measured for the wide variety of vehicle technology types in different states of deterioration. For example, the modelling of extremely low emissions (which can occur for short periods during moderate-power driving) with high relative accuracy might complicate the model to no advantage.

Model development

There were four main phases to the initial model development work:

Phase 1. The first phase of work consisted of collecting data and models from recent studies, analysing these data, developing a new dynamometer emission testing protocol, and conducting preliminary testing on a representative sample of vehicles (around 30).

Phase 2. This phase of work consisted of conducting tests on a larger representative sample of vehicles (approximately 320) using the dynamometer testing procedure developed during phase 1. This large collection of detailed vehicle operation and emissions data was used to iteratively refine and validate the working model.

Phase 3. This phase of work involved an examination of the interface between the developed modal emissions model and existing transportation modelling frameworks.

Phase 4. This phase of work consisted of incorporating additional vehicle/technology categories in order to better estimate emission inventories into future years, developing a graphical user interface (GUI) for the model, and holding a national workshop for potential model users.

Model structure

Vehicle categories

The basic building block of CMEM is the individual vehicle operating on a fine time scale (i.e. second-by-second). However, the model itself does not focus on specific makes and models of vehicles. The primary goal is the prediction of emissions during periods of several seconds for average, composite vehicles within each of the vehicle/technology categories specified in Table 5. Separate sub-models for each vehicle/technology category listed in Table 5 have been created. All of these sub-models have a similar structure, although the parameters used to calibrate each sub-model are very different. Each calibrated sub-model corresponds to a composite vehicle representing the characteristics of a particular vehicle/technology category.
Table 5: Vehicle/technology categories in CMEM.

<table>
<thead>
<tr>
<th>Category</th>
<th>Vehicle Technology Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal-emitting cars</td>
<td>1. No catalyst</td>
</tr>
<tr>
<td></td>
<td>2. 2-way catalyst</td>
</tr>
<tr>
<td></td>
<td>3. 3-way catalyst, carbureted</td>
</tr>
<tr>
<td></td>
<td>4. 3-way catalyst, FI, &gt;50,000 miles, low power/weight</td>
</tr>
<tr>
<td></td>
<td>5. 3-way catalyst, FI, &gt;50,000 miles, high power/weight</td>
</tr>
<tr>
<td></td>
<td>6. 3-way catalyst, FI, &lt;50,000 miles, low power/weight</td>
</tr>
<tr>
<td></td>
<td>7. 3-way catalyst, FI, &lt;50,000 miles, high power/weight</td>
</tr>
<tr>
<td></td>
<td>8. Tier 1, &gt;50,000 miles, low power/weight</td>
</tr>
<tr>
<td></td>
<td>9. Tier 1, &gt;50,000 miles, high power/weight</td>
</tr>
<tr>
<td></td>
<td>10. Tier 1, &lt;50,000 miles, low power/weight</td>
</tr>
<tr>
<td></td>
<td>11. Tier 1, &lt;50,000 miles, high power/weight</td>
</tr>
<tr>
<td></td>
<td>24. Tier 1, &gt;100,000 miles</td>
</tr>
<tr>
<td>Normal-emitting trucks</td>
<td>12. Pre-1979 (&lt;=8500 GVW)</td>
</tr>
<tr>
<td></td>
<td>13. 1979 to 1983 (&lt;=8500 GVW)</td>
</tr>
<tr>
<td></td>
<td>14. 1984 to 1987 (&lt;=8500 GVW)</td>
</tr>
<tr>
<td></td>
<td>15. 1988 to 1993, &lt;=3750 LVW</td>
</tr>
<tr>
<td></td>
<td>16. 1988 to 1993, &gt;3750 LVW</td>
</tr>
<tr>
<td></td>
<td>17. Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)</td>
</tr>
<tr>
<td></td>
<td>18. Tier 1 LDT4 (6001-8500 GVW, &gt;5750 Alt. LVW)</td>
</tr>
<tr>
<td></td>
<td>25. Petrol-powered, LDT (&gt; 8500 GVW)</td>
</tr>
<tr>
<td></td>
<td>26. Diesel-powered, LDT (&gt; 8500 GVW)</td>
</tr>
<tr>
<td>High-emitting vehicles</td>
<td>19. Runs lean</td>
</tr>
<tr>
<td></td>
<td>20. Runs rich</td>
</tr>
<tr>
<td></td>
<td>21. Misfire</td>
</tr>
<tr>
<td></td>
<td>22. Bad catalyst</td>
</tr>
<tr>
<td></td>
<td>23. Runs very rich</td>
</tr>
</tbody>
</table>

According to Barth et al., (2001), modelling at a higher level of detail is of limited value for two reasons. Firstly, at the second-by-second level there can be major fluctuations in driving patterns, with large short-term emissions consequences. Major fluctuations in throttle position are common in dynamometer tests using standard driving cycles, as the driver corrects for overshooting or undershooting the target speed. Information on the frequency and intensity of throttle fluctuations in actual driving is not readily available, as they depend on specific road and traffic conditions. Therefore, some time-averaging process is desirable in the model. Secondly, it would be difficult to develop a separate functions for all vehicle models based on measured parameters describing engine and emission control system behaviour, including rates of deterioration and failure for each vehicle. Instead, a generic characterisation of a composite vehicle within each vehicle/technology category is used, as specified in Table 5. The composite vehicle (in each category) is determined based on an appropriately weighted emissions average of all vehicles tested in the category. Generic parameters are then modelled as part of the composite vehicle emissions model. Using this generic approach, good modal emissions predictions are obtained for composite cars. Model accuracy also improves considerably with temporal aggregation.

Because many of the high emitting vehicles had disparate emission results when categorised by technology group, the high emitting vehicles were re-categorised into groups with similar emission characteristics. Grouping high emitters by emission profiles produced much more homogeneous groups than grouping by technology category. These characteristics include running lean, running rich, mis-firing, having a faulty catalyst, and running very rich.
Model structure

In CMEM second-by-second vehicle exhaust emissions are modelled as the product of three components: a fuel consumption rate \( (FR, \text{ in } \text{g s}^{-1}) \), an engine-out emission index \( \frac{g_{\text{emission}}}{g_{\text{fuel}}} \), and a time-dependent ‘catalyst pass fraction’ \( (CPF) \), which is defined as the ratio of exhaust to engine out emissions. \( CPF \) is usually a function of the air:fuel ratio and the engine-out emissions.

\[
\text{Exhaust emission} = FR \cdot \left( \frac{g_{\text{emission}}}{g_{\text{fuel}}} \right) \cdot CPF
\]

The complete modal emissions model is composed of six modules, as shown in Figure 12 by the six square boxes. The model requires two groups of input (the rounded boxes in Figure 12): (A) input operating variables and (B) model parameters. There are also four operating conditions in the model (the ovals in Figure 12): (a) variable soak time start, (b) stoichiometric operation, (c) enrichment and (d) ‘enleanment’. Hot-stabilised vehicle operation encompasses conditions (b), (c) and (d). The model determines in which condition the vehicle is operating at a given moment by comparing the vehicle power demand with threshold values. For example, when the vehicle power demand exceeds the enrichment threshold, the operating condition is switched from stoichiometric to enrichment. The model does not inherently determine variable soak time; the user must specify the time the vehicle has been stopped prior to being started. The model does, however, determine when the operating condition switches from a cold-start condition to a fully warmed-up condition. Figure 12 also shows that the operating conditions have direct impacts on the variables in Equation 7.

![Figure 12: CMEM structure (Barth et al., 2001).](image)

The vehicle power demand (1) is determined based on operating variables (A) and specific vehicle parameters (B). All other modules require the input of additional vehicle parameters derived from dynamometer measurements, as well as the engine power demand calculated by the model. The core of the model is the fuel rate calculation (4). It is a function of power demand (1), engine speed (2), and air:fuel ratio (3). Engine speed is determined based on the vehicle speed, the gear shift schedule and the power demand.

Model parameters

As discussed previously, separate sub-models for each vehicle category have been created. The sub-models all have a similar structure, but they differ in their parameters. Each sub-model uses three dynamic operating variables as input. These variables include second-by-second speed (from which acceleration can be derived), gradient, and the use of auxiliaries. In addition to these operating variables, each sub-model uses a total of 55 ‘static’ parameters in order to characterise the vehicle exhaust emissions for the appropriate vehicle category.
Definitions of the parameters and operating variables are given in Table 6.

**Table 6: CMEM input parameters (Barth et al., 2001).**

<table>
<thead>
<tr>
<th>Model Emissions Model Parameters and Variables</th>
<th>Readily-Available Parameters</th>
<th>Calibrated Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specific Vehicle Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( M ) - vehicle mass in lbs.</td>
<td>( k_0 ) - eng. fri. factor in kJ/(lit.rev)</td>
<td></td>
</tr>
<tr>
<td>( V ) - engine displacement in liters</td>
<td>( \varepsilon_1, \varepsilon_2 ) - drivetrain eff. coefficients</td>
<td></td>
</tr>
<tr>
<td>Idle - idle speed of engine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrsp - coastdown power in hp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S ) - eng spd./veh spd. in rpm/mph</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q_{\text{en}} ) - max torque in ft.lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_{\text{th}} ) - eng spd. in rpm @ ( Q_{\text{en}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{max}} ) - max power in hp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_p ) - eng spd. in rpm @ ( P_{\text{max}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_g ) - number of gears</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Generic Vehicle Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta ) - indicated efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varepsilon_1 ) - max. drivetrain eff.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R(L) ) - gear ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operating Variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \theta ) - road grade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{acc}} ) - accessory power in hp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v ) - speed trace in mph</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{\text{soak}} ) - soak time (min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( SH ) - specific humidity (grams H(_2)/lb.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a_{\text{CO}} ) - EO CO index coef.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a_{\text{HC}} ) - EO HC index coef.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{\text{HC}} ) - EO HC residual value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a_{\text{NOx}} ) - NO(_x) stoich index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a_{\text{NOx}} ) - NO(_x) enrich index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( FR_{\text{COI}}, FR_{\text{NOx}}, NO_{\text{Threshold}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Entrainment Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( h_{\text{max}} ) - max. HC(_{\text{max}}) rate in g/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( h_{\text{trans}} ) - trans. HC(_{\text{max}}) rate in g/SP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \delta_{\text{SP}a} ) - HC(_{\text{max}}) threshold value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( r_{\text{r}} ) - HC(_{\text{max}}) release rate in 1/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta_{\text{trans}} ) - ratio of ( O_2 ) and EHC</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Soak-time Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_{\text{cool}<em>{\text{CO}}}, C</em>{\text{cool}<em>{\text{HC}}}, C</em>{\text{cool}<em>{\text{NOx}}} ) - soak time ( \text{engine coef. for CO, HC, NO}</em>{\text{x}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_{\text{cool}<em>{\text{CO}}}, C</em>{\text{cool}<em>{\text{HC}}}, C</em>{\text{cool}<em>{\text{NOx}}} ) - soak time ( \text{Cat. coef. for CO, HC, NO}</em>{\text{x}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cold-Start Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{\text{CO}}, \beta_{\text{HC}}, \beta_{\text{NOx}} ) - cold start catalyst coefficients for CO, HC, and NO(_x) respectively</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta_{\text{cold}} ) - cold F/A equi. ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{\text{st}} ) - surrogate temp reach stoich</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( CS_{\text{HC}} ) - cold EO HC multiplier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( CS_{\text{NO}} ) - cold EO NO multiplier</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hot Catalyst Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{\text{CO}}, \Gamma_{\text{HC}}, \Gamma_{\text{NOx}} ) - hot max CO, HC, and NO(_x) catalyst efficiencies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( b_{\text{CO}}, b_{\text{HC}}, b_{\text{NOx}} ) - hot Cat CO, HC, and NO(_x) coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( c_{\text{CO}}, c_{\text{HC}}, c_{\text{NO}} ) - hot cat CO, HC and NO(_x) coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Enrichment Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \phi_0 ) - max F/A equi. ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_{\text{scale}} ) - SP threshold factor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 6, the model input parameters are firstly divided into two broad categories: 13 ‘readily available parameters’ and 42 ‘calibrated parameters’. The readily available parameters represent model inputs which can normally be obtained from public sources, and are further divided into specific vehicle parameters and generic vehicle parameters. The generic vehicle parameters are ones that may not necessarily be specified on a vehicle-by-vehicle basis, but are rather specified for entire vehicle classes. The calibrated parameters cannot be directly obtained from publicly available sources, rather they are deduced via testing. This group of parameters is further divided into two sub-sets: an ‘insensitive set’ (23 parameters) and a ‘sensitive set’ (19). In the insensitive set, the model parameters are either known in advance (e.g. fuel and engine-out emission parameters) or have a relatively small impacts on overall vehicle emissions (e.g. enrichment parameters). The parameters in the sensitive set need to be carefully determined. There are three sub-sets of sensitive parameters: (i) a cold-start subset, (ii) a hot stabilised catalyst subset and (iii) an enrichment parameters subset.

**Calibration**
As the model was developed, each test vehicle was individually modelled by determining all the parameters described in the previous section. The readily available parameters were obtained for each vehicle, and the calibration parameters were determined through a detailed procedure using the measured emissions results for each test vehicle. Depending on the specific parameter, the calibration values were determined either directly from measurements, based on several regression equations, or were based on an optimisation process.

Vehicle ‘compositing’

Each of the vehicles tested during the experimental phase was modelled using the calibration process. However, the primary modelling goal was to predict detailed emissions for each of the average, composite vehicle categories listed in Table 5. Thus, a procedure was developed to construct a composite vehicle to represent each of the different categories. This procedure is described by Barth et al. (2001).

High-emitting vehicles

Suspected high-emitting vehicles were tested using a number of different methods. Based on their emission results, the vehicles were classified either as ‘high-emitting’ or ‘normal-emitting’ using a set of cut points. The high-emitting vehicles were further divided into different categories based on the characteristics used to classify normal emitters (e.g. emission certification level - Tier 0, Tier 1). However, these categories did not work well, simply because the vehicles in the groups had very different emission characteristics. The vehicles were therefore regrouped according to the physical mechanism of emission control system failure. Four types of high emitter were determined, and for each a profile was determined in relation to exhaust CO/HC/NOx levels:

**Type 1: Operates lean at moderate power.** This type of high emitter has a fuel ratio that is chronically lean or goes lean during transient operation calling for moderate power. CO and HC emissions are typically low, but the NOx emissions are high. A physical failure mechanism leading to this type of behaviour is not easy to identify. Improper signal from the oxygen sensor or improper functioning of the electronic engine control are possible causes.

**Type 2: Operates rich at moderate power.** In this case, the fuel ratio is chronically rich or goes rich during transient moderate-power operation. The engine-out hydrocarbons typically remain at normal levels. Under these conditions, the CO emission index and catalyst pass fraction are high, resulting in high exhaust CO emissions. There are many possible failure mechanisms resulting in enrichment during closed loop operation. However, the mechanism here must also leave engine-out HC emissions in the normal range (i.e. there can be enrichment but not misfire). One possible cause would be a leaking exhaust line allowing air to before the oxygen sensor, resulting in the sensor demanding more fuel from the injectors.

**Type 3: High engine-out HC emissions.** The third type of high emitter involves a high engine-out emissions for HC and mild enrichment (high engine-out CO and high CO catalyst pass fraction). Catalyst performance is also poor. The profile for this type of high emitter consists of moderate-to-high exhaust CO, very high HC, and moderate-to-low NOx. Excess engine-out HC is probably caused by incomplete combustion in one or more cylinders (misfire), from a physical mechanism such as a faulty spark plug or partial obstruction of an injector. Catalyst performance is also poor, and not only when hydrocarbons are high. This is likely due to deterioration caused by the combination of high engine-out HC and high oxygen levels. This mixture readily burns in the catalyst, causing very high temperatures and catalyst deterioration.

**Type 4: Poor catalyst performance for all three pollutants at moderate power.** High exhaust emissions of all pollutants typifies Type 4 emitters. This type involves more than one behaviour, with chronically poor catalyst performance due to a burned-out or missing catalyst, or transiently poor catalyst performance in moderate-power driving. Type 4 malfunction is distinguished from Type 3 because engine-out HC is normal, or only slightly high, and from Type 2 because there is no or only slight enrichment at moderate power. For this type, in almost all cases all three pollutants are high.
3.3.3 Validation

CMEM validation was conducted by comparing the model with emission test results which were not directly used in its development, and thus provided independent test data. The aggregate exhaust emissions of CO₂, CO, HC, and NOₓ for the 26 composite vehicles were calculated. Overall, the composite vehicle validation results were very good, with no significant bias.

A second validation was conducted on measured and modelled second-by-second CO₂, CO, HC, and NOₓ emissions for individual vehicles. The model was not intended for use as a second-by-second model for prediction of individual vehicles. However the second-by-second evaluation provided insight into the bias and variability of the model. In general, lower vehicle-to-vehicle variability was found on the decelerations and the cruise events for both normal emitters and high emitters. Normally operating vehicles showed a tendency towards an over-prediction of emissions at the start of acceleration events followed by an under-prediction of emissions at the end of acceleration events. There was a tendency to slightly under-predict NOₓ emissions from high-emitting vehicles on the cruise sections of driving cycles.

CMEM continues to be expanded and enhanced. For example, a method has been developed to determine emissions for future vehicle types based on the physical parameter nature of CMEM, and work has been undertaken to incorporate heavy-duty vehicles in the model. Other potential improvements include improved modelling of variable soak time starts and the effects of auxiliaries, and integration with transportation models (Barth et al., 2001).

3.3.4 Software description

The CMEM software is well documented by Barth et al. (2001). The model is available as executable code for both the PC environment (running from a DOS command line) and the UNIX environment. A more user-friendly, graphical interface is available in Microsoft Access. CMEM can be ordered via internet at a cost of US$20.

Executable code

The CMEM executable code takes two forms – a ‘core’ model and a ‘batch’ model. The core model uses two input files and outputs two emission files. A control input file specifies the vehicle category to be modelled and the soak time prior to the model run. The other input is a second-by-second vehicle activity file (the driving pattern). The parameters in the vehicle activity file include speed, acceleration, gradient and use of auxiliaries such as air conditioning. One resulting output file provides exhaust emissions and fuel consumption on a second-by-second basis. The other output file is a vehicle summary file. The emissions output file includes time, speed, HC, CO, NOₓ, and fuel use. Other second-by-second parameters (e.g. CO₂, air:fuel ratio, etc.) can also be selected for output via the control file. The batch executable code allows the user to obtain emission data for multiple vehicles (from a variety of categories) with different trajectories specified in the vehicle activity file. The batch model is otherwise very similar to the core model.

Both forms of the executable code were written in C++. The core form of the model has been tested with up to 50,000 seconds of trajectory data. The batch form of the model has been tested with up to 100 vehicles, each having approximately 25,000 seconds of trajectory data. addition to the executable code, demo input and output files for both forms of the CMEM model are provided.

Microsoft Access version

In order to make CMEM easier to use, a graphical user interface (GUI) has been coded in Visual Basic to run in Microsoft Access. The CMEM Access version is equivalent to the batch version of the executable file. Serving as the main menu of the GUI is the form shown in Figure 13. This form appears when CMEM-Access is first opened. From this form, it is possible to setup the input information (e.g. vehicle data, activity information), run the model, and then observe the output through either tables or graphs.

16 http://pah.cert.ucr.edu/cmem/
Vehicle Data

The vehicle data input form is shown in Figure 14. Here, the user specifies the characteristics of different vehicles, and assigns each of them a unique identification number. It is then possible to assign each vehicle to a fleet. For each vehicle, the appropriate CMEM vehicle category must be assigned.

Activity Data

As with the vehicle data file, the vehicle activity file is represented as a form in the CMEM-Access version. This form is shown in Figure 15. From this form, it is possible to create and/or edit the activity data directly.
Once the vehicle data and activity data are set, the model code needs to be executed. This is accomplished simply by clicking the ‘Calculate’ button on the main menu. It is possible to generate several types of output:

- Second-by-second emissions results
- Emissions summary results
- Fleet emissions graph
- Fleet summary result

3.4 ADVISOR

3.4.1 Background

ADVISOR (Advanced vehicle simulator) was originally developed collaboratively by the US Department of Energy and the US National Renewable Energy Laboratory (NREL), for the modelling of fuel cell and hybrid power trains, including the effects of these advanced vehicle concepts on vehicle performance, economy and emissions. In the summer of 2003, NREL partnered with AVL to further commercialise the simulation tool. Whilst this transfer enabled the rapid development of the tool, the model has subsequently moved from a freely available research tool, to a commercial product. The current cost of this simulation tool is 5000 euro.

ADVISOR operates on fundamental principals of vehicle dynamics and end user provided input data describing the engine’s performance and the vehicle characteristics (Markel et al., 2002). Whilst it is widely used within the motor industry to derive characteristics from existing vehicles, its strength lies in the prediction of the performance of concept vehicles. ADVISOR is routinely used to map fuel consumption, exhaust emissions, acceleration performance, and drivability.

3.4.2 Modelling approach

In general, the model requires a two step input. Firstly it requires a definition of the vehicle using measured or estimated component and overall vehicle data. Secondly it requires a speed-time trace, combined with road gradient, over a pre-defined test route. ADVISOR is then used to simulate a drive over this test route, and
derives as output various torque measurements, speed, and component power consumption. Under this configuration, ADVISOR allows the user to answer a range of typical questions:

- Was the vehicle able to follow the trace?
- How much fuel and/or electric energy were required in the attempt?
- What were the peak powers delivered by the drive train components?
- What was the distribution of torques and speeds that the piston engine delivered?
- What was the average efficiency of the transmission?

These virtual test results are routinely validated against samples of full scale real world measurements, in order to evaluate the accuracy of the modelling.

The detailed modelling of vehicle emissions may be undertaken with Advisor 2000 and later revisions. ADVISOR is written in the widely used MATLAB/Simulink software environment. ADVISOR is thus empirically based, and relies on drive train component input/output relationships measured under laboratory conditions, and data collected in steady state (e.g. constant torque and speed) tests, with subsequent correction for transient effects, such as the rotational inertia of drive train components.

ADVISOR can thus be used to:

- estimate the fuel economy of concept vehicles
- learn about how conventional, hybrid, or electric vehicles use (and lose) energy throughout their drive trains
- compare tailpipe emissions produced on a number of cycles and different conditions
- evaluate a control logic for hybrid vehicle's fuel converter
- optimize the gear ratios in transmission to minimize fuel use or maximize performance, etc.

3.5 MOVES

3.5.1 Background

MOVES2004 is the first release version of the USEPA MOtor Vehicle Emission Simulator. It is designed to be used to estimate inventories and projections through to 2050 at the county level for road transport energy consumption, and is currently restricted to the estimation of nitrous oxide (N₂O), and methane (CH₄) emissions. It is equipped with a full suite of default data to estimate these results for the entire United States. It also includes an interface with an updated version of Argonne National Laboratory’s Greenhouse gases, Regulated Emissions, and Energy uses in Transportation (GREET) model to include ‘well-to-pump’ estimates of energy consumption and emissions. Future versions of the model are planned to estimate non-highway mobile source emissions, estimate criteria pollutant emissions, and operate at smaller geographic scales (Koupal et al., 2005).

MOVES2004 was developed from the bottom-up, taking into account the needs of mobile source model users and recommendations on how to improve these models. As a result, MOVES2004 implements a number of novel approaches including: modelling energy consumption, N₂O and CH₄ explicitly; employing a modal emission rate approach as a lead-up to finer-scale modelling; modelling a broad array of advanced technology vehicles; explicitly modelling periods of extended idling (e.g. heavy-duty ‘hostelling’); relying primarily on second-by-second data to develop emission rates; and including well-to-pump energy emission estimates to enable life-cycle analysis.

Second-by second emission data were derived from a range of sources including the US I/M240 test programme, and several of those test programmes used to derive the average-speed related emission factors incorporated within the MOBILE6 model. Supplementary data were derived from non-EPA test programmes.

17 Full details of the MOVES model are available on the dedicated MOVES website - http://www.epa.gov/otaq/ngm.htm
A review of instantaneous emission models for road vehicles

underaken by California Air Resources Board (CARB), Coordinating Research Council (CRC), The New York State Instrumentation/Protocol Assessment Study, North Carolina State University, University of California Riverside College of Engineering Centre for Environmental Research and Technology, Environment Canada, Texas Department of Transportation and the University of Texas, West Virginia University and test results from the Arizona, British Columbia and Colorado I/M programmes. Emission data gaps were subsequently in-filled using the Fuel Consumption Modelling of Diesel, Motorcycle, and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE).

This first version of MOVES included a range of fuels including gasoline (conventional, E10 and reformulated), diesel (conventional, bio diesel and Fischer-Tropsch), CNG, E85, M85, LPG, and electricity. It is intended that the model will be extended to include hydrogen (gaseous and liquid), once well-to-pump pathway inputs become available. The model is able to employ these fuels to a range of vehicle technologies including conventional internal combustion (all fuels), advanced internal combustion (gas and diesel), moderate hybrid-electric (gas and diesel), full hybrid-electric (gas and diesel) and dedicated electric. Fuel cell and hybrid fuel cell-electric will be added in conjunction with the addition of hydrogen to future versions of the model.

Significantly the model incorporates a graphical user interface, using a relational database to store underlying data, and the calculation of total energy and emission inventories rather than simply calculating per-mile emission factors.

The next version of MOVES was planned for release in 2006. It was envisaged that MOVES2006 would complete the on-road component of the model, adding HC (including non-exhaust emissions), CO, NOx, PM, toxics, CO2, NH3 and SO2. It is envisaged that MOVES2006 will eventually replace the existing US EPA average-speed based MOBILE6.

The current MOVES2004 and the upcoming MOVES2006 models will make use of a second-by-second databases of emission rates (grams per second). However, within those databases the individual bins (cells) are based upon a calculated Vehicle Specific Power (VSP), on a second-by-second basis. Thus, the driving cycle (speed and acceleration at each second of operation) must initially be converted into a number of VSP bins. Therefore, knowledge of the VSP bin for each second of operation, allows the derivation of vehicle emissions (or fuel consumption) for each second. Although the model is currently in a beta testing phase, it is considered that the model should produce reasonable estimates at both the individual link and the network scales. All that is needed is the appropriate distribution of VSP bins. The standard output will be grams per hour.
4 ‘Adjusted’ models

Previous Chapters of this Report have dealt with ‘unadjusted’ models in which the dynamic distortion of the emissions signal has not been taken into account during the model development. This Chapter of the Report describes the potential problems associated with this approach, and describes two similar models, developed by TUG and EMPA, in which an attempt has been made to correct the emissions signal for light-duty vehicles. The main difference between the TUG and EMPA models is that the latter is more detailed, but requires the dimensions of the exhaust gas system of the tested cars and measured modal data on the exhaust gas volume flow. The TUG model uses a simpler approach which can be applied using the data normally recorded during chassis dynamometer tests.

4.1 Background

4.1.1 Modelling errors

A number of potential sources of error in the unadjusted instantaneous modelling approach have been identified. These sources of error are well documented (e.g. Joumard et al., 1998; Sturm et al., 1998; Latham et al., 2000; Weilenmann et al., 2001). Sturm et al. (1998) summarised studies relating to a number of these sources of error, with particular reference to models based on speed and acceleration. The aspects of modal emission modelling which where covered included the following:

(i) The types of cycle used to create emission matrices. The experience gained during the development of various emission models suggests that they may not accurately predict the emissions associated with vehicle operations which are different to those used in their development. Models are often based on cycles with ‘low dynamics’ (such as those defined in legislation), and might produce more accurate results if the emission database which it currently uses is replaced by ones based on the types of vehicle operation for which they are trying to predict.

(ii) The parameters used to describe vehicle operation. Some models define the emission matrix according to speed and acceleration, whereas others use the parameters speed and speed × acceleration. Also, acceleration values can be calculated in a number of different ways from the speed profile.

(iii) The grid size in the emission matrix. Typical increments in an emission matrix are 5-10 km h⁻¹ for speed, 0.1-0.4 m s⁻² for acceleration, and 1.3-5.0 m² s⁻³ for speed × acceleration. With smaller increments the operational conditions of the modelled driving pattern can be better represented, but proportionally more of the emission matrix cells will remain empty unless a wider variety of driving cycles are used in the development of the model. Larger increments allow more matrix cells to be filled with emission data, but subtle alterations in vehicle operation are not taken into account.

(iv) The type of interpolation scheme. Emission values are stored in a matrix with a given grid size, and the values in each cell relate to a range of operational conditions. An interpolation scheme can be used to calculate emission values for operational conditions which lie within this range. The way in which the emission values are interpolated between the matrix values can lead to different emission results.

It was concluded by Sturm et al. (1998) that the choice of driving cycles used to develop emission matrices is an important determinant of a model’s accuracy, but neither the parameters used to describe operation, the grid size, nor the use of an interpolation scheme resulted in any improvements in accuracy.

There are clearly deficiencies in the modal modelling approach which cannot be entirely resolved by changing the emission factors or the way in which the models operate. It may be that any attempt at a comparison between emission models predictions and measurements is confounded by the general variability in the emission rates of the vehicle samples used in the models and the vehicle samples used in the measurements. Because the vehicle fleet is so large, and only a tiny proportion of it can be sampled, this will always lead to problems, to a greater or lesser extent, where emission model predictions (based on one sample of vehicles) are being compared with emission measurements (based on a second sample).
A number of further suggestions for improving modal models have been proposed. Firstly, evidence suggests that catalysts tend to exhibit on/off control, and emission levels from catalyst-equipped vehicles are much more sensitive to operating conditions than those from non-catalyst vehicles. Under particular operating conditions the catalyst may be working at its maximum efficiency, but for slightly different conditions the conversion efficiency may be low. For example, measurements on Euro I vehicles by Joumard et al. (1998) showed that for engine loads (the actual power divided by the maximum power at a given engine speed) greater than 75%, instantaneous CO emissions can be 20,000 times higher than for lower loads (Figure 16). Over an entire motorway driving cycle around 90% of the total CO emissions occurred during only 15% of the time. This feature of catalyst operation would have contributed to the observed sensitivity.

Figure 16: Instantaneous CO emissions from a catalyst car versus engine speed and load over a motorway cycle (Joumard et al., 1998).

Joumard et al. (1998) argued that efforts should concentrate on extreme engine operating conditions, particularly for catalyst-equipped vehicles, and this approach has been further investigated in France (Lacour et al., 2000). However, the work conducted so far indicates that models which treat extreme events separately provide no improvement in accuracy over existing instantaneous models, or even over average speed models. Research in Switzerland (INFRAS, 1998) has indicated that the introduction into models of a parameter relating to gear-shift behaviour could help to reduce the variability of the emission values in matrix cells, and indeed the definition of gear-shift behaviour has been an important element of modern power-based models such as PHEM.

However, one of the most fundamental problem relating to instantaneous emission modelling is that it is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and the emissions and fuel consumption values recorded in short time steps might not be successfully allocated to the associated operating conditions. The reasons for this are discussed in the following sections, and the results have obvious implications for the development of emission models based on instantaneous vehicle operation.

### 4.1.2 Signal time delays and smoothing

Because of the time required to transport the exhaust gas to the analysers, and the actual response time of the analysers themselves, the emission signals measured in a test are delayed relative to their time of formation (and hence relative to the driving cycle). Although this effect is well known, methods for correcting this misalignment do not appear to be widely reported (Weilenmann et al., 2001; Atjay and Weilenmann, 2004).
Usually, the time delay has been taken into account by shifting the entire measured emission signal backward by a fixed number of time steps.

However, Weilenmann *et al*. (2001) have shown that, when raw exhaust gas is being sampled, the delay is not constant, and varies by more than one second depending on the gas flow rate in the exhaust. Significant changes in the transport time delay occur during a transient cycle due to the varying speed of the exhaust gas flow. In general, a low flow rate at low engine speed and low engine load causes a long delay, whilst a rapid flow rate at high engine speed and high load causes a short delay (Atjay and Weilenmann, 2004). The variation in transport time is particularly high for light-duty vehicles with petrol engines, since the gas transport through these engines becomes low when the throttle is closed at idle or near-idle (Weilenmann *et al*., 2003).

Correcting the time delay by shifting the entire emission signal be a fixed number of seconds is clearly going to mean that emission events are temporally misaligned with the speed data, resulting in model inaccuracy. Over a transient driving pattern engine load varies every second, and hence there will inevitably be moments when the emission signal preceded the generation of the emission itself. The damping of the raw exhaust signal means that, in general, the ‘real’ emission peaks will be underestimated, and the emission troughs overestimated. Even if no original emission has occurred in a given instant, a model can produce a value because of the temporal spreading of the emission peaks (Weilenmann *et al*., 2001).

In addition to being delayed, the exhaust gas is mixed in the exhaust system and sampling lines during transport to the analysers. This results in a general flattening of instantaneous emission peaks, often over a periods of more than one second. The dynamics of the mixing, and the flattening of the emission peaks, also depend on the gas flow rate, and the situation is even worse when exhaust gas is being sampled using a dilution tunnel (Weilenmann *et al*., 2001). As a consequence, emission peaks often appear to bear no relationship at all to the operation of the vehicle.

The phenomena of time delay and damping have been illustrated by Weilenmann *et al*. (2001). In the experiment shown in Figure 17, a non-catalyst petrol car was mounted on a chassis dynamometer and a gas injection inlet was installed directly after the exhaust manifold. The engine was operated in three steady-state modes at loads associated with idling (test 1), urban driving (test 2), and inter-urban driving (test 3). The exhaust volume flow ranged from 0.005 m$^3$s$^{-1}$ during idling to 0.130 m$^3$s$^{-1}$ during operation at the highest load. During the driving the gas (oxygen) valve was opened and closed several times (resulting in a step input) and the gas analyser response was recorded. The Figure clearly shows that the analyser signal is delayed, and that the delay between the emission peak and the signal peak is dependent on the exhaust gas flow rate (which is varying constantly). Also, the concentration recorded at the analyser takes much longer to reach its maximum value than the input signal.

In modern petrol cars equipped with a three-way catalyst, oxygen peaks occur in fuel cut-off situations. Figure 18 shows a two-second fuel cut-off (~418 s) at 60 km h$^{-1}$ in such a car. In the top graph the raw exhaust valve signal 3 is represented by the solid line, and the raw exhaust analyser oxygen signal is represented by the dashed line. The bottom graph shows the signal recorded by the analyser in the dilute exhaust. The fuel cut-off creates an oxygen peak of 1.2 seconds at the lambda sensor downstream of the catalyst. The raw gas analyser response follows at time 425 s, and is much smaller. This shows that the dynamics of the raw exhaust gas line and the analyser are too slow for a peak of this duration to be measured accurately. In the dilute gas measurement the peak occurs at 437 seconds, and is even wider and flatter than the raw exhaust peak.

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

Therefore, even if modal emission models were constructed using raw exhaust measurements, such results indicate that there would clearly be problems matching an emission signal in any given second to the appropriate speed or acceleration measurement. Figure 18 indicates that the signal obtained from measurements in a dilution tunnel bears little relation to the real signal. In models based upon measurements on dilute exhaust, the aforementioned problems will be amplified.
Figure 17: Results of gas injection tests; the valve signal is represented by the solid line, the analyser oxygen signal is represented by the dashed line (adapted from Weilenmann et al., 2001).

Figure 18: Oxygen concentrations after a two-second fuel cut off. (adapted from Weilenmann et al., 2001).

This is illustrated for a single petrol non-catalyst vehicle and the MODEM model in Figure 19. The measured CO emission profile was obtained using the diluted exhaust gas, and the modelled CO emission profile was obtained using an emission matrix based on the measured profile alone. Although points A and B have similar speed and acceleration values, point A corresponds to a CO emission rate of almost 3,000 g h\(^{-1}\), whereas point B corresponds to an emission rate of less than 1,000 g h\(^{-1}\). It is likely that this variability in the emission rate associated with given operational parameters will occur throughout the emission profile, and therefore the model will tend not to pick up the peaks and troughs of the (already highly damped) emission trace. This would still probably occur, though hopefully to a much lesser extent, even if a ‘true’ emission profile could be obtained (Boulter, 2001).
Figure 19: CO emission profile measured for a single vehicle compared with the emission profile predicted by MODEM using an emission matrix based on the measured profile (Boulter, 2001).

Clearly, advances in the field of modal emission modelling will not be forthcoming until realistic continuous emission data are available, and efforts have been made to reduce the dynamic distortion of the emission data (Weilenmann et al., 2001; Atjay and Weilenmann, 2004; Atjay et al., 2005). Specifically, compensation must be made for the variable time delay and the smoothing of the emissions signal.

4.2 The EMPA model

4.2.1 Background

Work on the instantaneous modelling of emissions from modern light-duty vehicles has been conducted in ARTEMIS by the Swiss research institute EMPA. Some of this work was described in the previous Section. Using advanced measurement and modelling techniques, which are reliant upon knowledge of a number of test parameters, high-frequency measurements, and the solving of a series of differential equations, it is possible to estimate emissions from individual vehicles over short time scales. Weilenmann et al. (2001) have developed a mathematical model of the measurement system which can then be ‘inverted’ or solved in order to reconstruct the original emission signal in the exhaust pipe from the one measured at the analyser. This process increases in complexity with the level of exhaust dilution used. It is least complex when emissions are recorded at the exhaust manifold, more complex when emissions are recorded in the exhaust pipe, and the most complex when a dilution tunnel is used. The approach was further developed to compensate for the dynamics in a dilute sampling system (CVS) and initial steps were taken towards developing a new instantaneous model (Weilenmann et al., 2003; Atjay et al., 2005).

4.2.2 Modelling approach

The model proposed by Atjay et al. (2005) is illustrated schematically in Figure 20. A first subsystem describes the gas transport from the exhaust pipe to the mixing point. This transport is described by a time delay which is dependent on the volume flow rate of the car exhaust gas, and a turbulent mixing which is modelled as a linear time-varying system. Since the exhaust volume flow varies over time, it must be known. The volume flow varies between 3 l s⁻¹ and 150 l s⁻¹ for a typical 2-litre car. In the case of the EMPA sample lines between the exhaust pipe and the mixing point, which have a volume of 50 litres, the transport lasts between 0.3 and 16 seconds. The exhaust signal is transformed at the mixing point, and a mass balance is required. The second subsystem describes the transport through the dilution tunnel. It is modelled as a time delay and a second-order dynamic for the turbulence. Since the volume flow is almost constant here, the
parameters of the system are time-invariant. Finally, the same approach is used to describe the transport in the narrow sample lines carrying the gas from the CVS tunnel to the analysers. The dynamic response of the analysers is also added. This is the third subsystem and, it is again modelled as a time delay and a second-order linear system.

![Figure 20: Structure of the EMPA model for CVS systems (Atjay et al., 2005).](image)

For the parameterisation of the model, several gas bottle tests were carried out. The tests were run with a Euro II petrol vehicle with three-way catalyst, as shown in Figure 21. The car was driven at different steady-state points for each test. For the identification of system's parameters, concentration step signals were generated by injecting calibration gases from bottles at the input of each of the CVS subsystems mentioned above and the emission step responses were measured at the corresponding output by fast sensors (lambda sensor or NOx sensor). Finally, the model parameters were identified by fitting the model output to the measured signal by least squares (Atjay et al., 2005).

![Figure 21: Set-up for the measurements necessary for modelling (Atjay et al., 2005).](image)

To reconstruct the emission signal at the end of the car from the signal at the analyser, the overall model must be inverted. This inversion is performed subsystem by subsystem. In each case, the input of one subsystem must be determined from the output of another subsystem. This process is rather complex, and is described by Atjay et al. (2005). The quality of the overall inversion is shown in Figure 22 for a NOx signal. The top graph shows the NOx signal at the analyser. In the bottom graph the solid line represents the reconstructed signal using the model of the dilution system, and dashed the dashed line represents the reference signal at exhaust pipe, obtained from raw gas measurement. The original peak, which lasts more than 12 seconds in the diluted measurements, can be reconstructed to a peak of about 3.5 seconds duration. This is a very good result. However, the quality is roughly half as good as for the raw signal, whose peak lasts just 1.7 seconds.

\[
\begin{align*}
  u(t) & = \text{exhaust gas concentration at the exhaust pipe (ppm)} \\
  y_1(t) & = \text{exhaust gas concentration at the mixing point (ppm)} \\
  \bar{y}_1(t) & = \text{gas concentration after the mixing with the dilution air (ppm)} \\
  y_2(t) & = \text{gas concentration at the end of the dilution tunnel (ppm)} \\
  y(t) & = \text{signal at the analyser (ppm)}
\end{align*}
\]
As a first step in the development of a practical emission model, the emission signals were mapped on a classical speed and speed x acceleration map using 1 Hz data, as in most older models for passenger cars. Secondly, the emission signals, corrected using the method described above, were mapped using speed and speed x acceleration on a 10 Hz basis. In a third step, the emissions were mapped applying the same approach to brake mean effective pressure ($p_{me}$) and engine speed ($n$). Brake mean effective pressure can be considered as normalised engine torque, and is therefore useful for the comparison of different cars. The advantage of this new alternative of mapping derives from the fact that the influences of the vehicle loading and the gearshift may be taken into account (Atjay et al., 2005). To qualify model accuracy, the emissions calculated by each model for a certain cycle (not used for the model parameterisation) were compared with the measured emissions. This was done by choosing different cycles as verification cycles and for several cars. The quality of the predictions for the different models is shown in Table 7 for a pre-Euro I petrol vehicle, a Euro III petrol vehicle and a Euro II diesel vehicle.

**Table 7**: The correlation coefficients between measured and simulated emission factors for different categories of vehicles and mapping (Atjay et al., 2005).

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Map used</th>
<th>CO</th>
<th>CO₂</th>
<th>HC</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Euro I petrol</td>
<td>v-v*a without time</td>
<td>0.95</td>
<td>0.994</td>
<td>0.94</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>v-v*a with time correction</td>
<td>0.98</td>
<td>0.994</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>pme-n with time correction</td>
<td>0.99</td>
<td>0.991</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td>Euro III petrol</td>
<td>v-v*a without time</td>
<td>0.24</td>
<td>0.987</td>
<td>0.32</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>v-v*a with time correction</td>
<td>0.69</td>
<td>0.994</td>
<td>0.59</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>pme-n with time correction</td>
<td>0.73</td>
<td>0.995</td>
<td>0.64</td>
<td>0.50</td>
</tr>
<tr>
<td>Euro II diesel</td>
<td>v-v*a without time</td>
<td>0.73</td>
<td>0.987</td>
<td>0.93</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>v-v*a with time correction</td>
<td>0.89</td>
<td>0.992</td>
<td>0.95</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>pme-n with time correction</td>
<td>0.90</td>
<td>0.994</td>
<td>0.96</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The prediction quality improved significantly from the first model to the third model. For diesel Euro II cars and pre-Euro I petrol vehicles the prediction quality of the third model was good. However, the prediction quality for the petrol vehicles with a catalyst (Euro III) was far from satisfactory. This was expected, since for these cars high emissions often arise during transient manoeuvres. As these models do not include the dynamic behaviour of the engine, a dynamic emission model is needed.

It follows that the emission map should be extended by using a new variable to express dynamics. Such a variable might be the derivative of the manifold pressure, or the derivative of torque. Emission peaks for HC are caused by peaks in the derivative of manifold pressure, and cannot be predicted from engine speed or
vehicle velocity. Another element, which is of great importance in terms of the emissions level, is catalyst behaviour, and the catalyst has its own dynamics (i.e. oxygen storage). Thus, besides the engine model, a model for oxygen storage in the catalyst has to be added. The inclusion of a dynamic variable and/or a catalyst model should lead to improvements in the existing model (Atjay et al., 2005).

4.2.3 Validation

A validation exercise has only been performed using the vehicle tested for model parameterisation, as described in the previous Section. The vehicle was driven over a US FTP\textsuperscript{18} cycle. No gas was injected, but the pollutant concentration signals of the car were measured at the exhaust pipe using fast sensors, and these were used as input to the model. There was a very close match between the measured and predicted signals at the analysers.

4.2.4 Software description

No commercially available software has been produced by EMPA so far.

4.3 PHEM (PC part)

4.3.1 Background

The passenger car part of PHEM was developed as a flexible instantaneous emission model for predicting fuel consumption and emissions for any single type of car, as well as for average car fleets, based on measurements from the ARTEMIS project. The model requires the user to input a driving pattern, and can also take into account the vehicle load, the road gradients and the gear-shift behaviour. The only description in English of the car part of the model appears to be that given by Zallinger et al. (2005a).

As well as the use of engine emission maps rather vehicle speed and acceleration maps, and transient corrections in addition to steady-state emission factors for diesel vehicles (aspects which were described in Section 3.1), the model includes correction functions to compensate for mixing effects and variable transport times in diluted and undiluted sampling, and subroutines to estimate cold-start effects. However, transient corrections are not yet available for petrol vehicles equipped with a three-way catalyst.

4.3.2 Modelling approach

As in the HDV part of PHEM, for a driving pattern and road gradient specified by the user the effective engine power is calculated every second based upon the driving resistances and losses in the transmission system. The actual engine speed is simulated using the transmission ratios and a gear-shift model, and the emissions are then interpolated from engine maps. However, this method was developed for HDVs, for which the engines are usually measured on test beds. The main problem of applying PHEM to the simulation of passenger cars was finding a suitable method for deriving engine emission maps from measurements on the chassis dynamometer. Steady-state engine maps can be measured on the dynamometer with sufficient accuracy, but such measurements were not included in the basic test programme. As a result, an established instantaneous modelling method had to be applied to determine engine emission maps from transient vehicle tests. In order to generate more reliable predictions, the instantaneous emission signals were corrected for the time delay of the analyser and the variable transport time in the measurement system.

The approach used to correct the instantaneous emission signal is similar to that presented in Section 4.2, with the exhaust gas sampling system being divided into three parts relating to transport, mixing and analyser effects. The transport of one emission component (HC) was investigated using a 3-D CFD\textsuperscript{19} model. As before, the inversion of the exhaust gas transport model was conducted in turn for each of the three parts of the system. The variable time delay in the exhaust pipe was determined as a power function of the exhaust gas volume flow. This function proved to be a simple solution, since the exhaust gas volume flow can be

---

\textsuperscript{18} FTP = Federal Test Procedure.
\textsuperscript{19} CFD = computational fluid dynamics.
calculated via instantaneous emissions and the CVS total volume flow. By using the exhaust gas volume flow as a variable, the function is identical for all sampling systems. Only the coefficients of the function are different, and these depend on the total exhaust pipe length for the vehicle and the specific CVS system. The corrections significantly improved the quality of the instantaneous emission signals, and hence the instantaneous emission model (Zallinger et al., 2005a).

The resulting instantaneous data on engine power, engine speed and exhaust gas emissions were then used to create the engine maps for the model. The emission values for the engine map were created from the measured driving cycles using an interpolation method. Figure 23 gives a schematic picture of the allocation of emission values to the effective engine power and the actual engine speed.

![Figure 23: Derivation of engine emission maps for passenger cars in PHEM (Zallinger et al., 2005a).](image)

The method is capable of simulating the fuel consumption and emissions for any driving cycle and any vehicle configuration. As the modelling approach involves parameters relevant to combustion and to the engine control unit, it was possible to dynamic correction functions to take into account the influence on emissions of different transient driving conditions. The transient corrections were derived from empirical functions which transformed the emission levels from each single point in the engine map to the emission levels which would be expected under the actual transient engine load during the driving cycle being modelled.

### 4.3.3 Validation

The validation of the model for the simulation of different road gradients was undertaken by Zallinger and Hausberger (2004). Some of the validation results for different driving cycles are described below. With PHEM, it is possible to simulate emission factors for average pre-Euro I to Euro IV diesel and petrol cars, as well as for single specific cars. For the validation, the average emissions measured for five Euro II diesel cars over 12 real-world cycles were compared with model predictions for an average car of the same type. The engine map for the average Euro II car was created using the instantaneous measurements from eight cars. In the simulation the average vehicle characteristics (mass, drag coefficient, etc.) were used in conjunction with the average engine map. Since there were no second-by-second measurements for PM, the PM emission map was assumed to have the same shape as the HC map; only the absolute values were adapted to meet the measured PM emissions with the lowest square of deviation. The establishment of dynamic PM mass emission maps and particulate number emission maps from instantaneous measurements of these parameters has already been tested successfully, but average emission maps are not available yet.
The results of the average diesel car showed a high level of accuracy for fuel consumption and NOx (Figure 24), and adequate results for HC, CO and PM, even without transient correction functions. Similar results were gained for all single diesel cars. Since the engine maps were created from a completely different set of measurements than the simulated cycles in terms of gear shift rules and acceleration values, the model for diesel cars seems to be very reliable.

![Figure 24: Simulation quality for the emission factors of the average Euro II diesel car with PHEM.](image)

The same validation method was used for petrol vehicles. In this case, the average emissions of six Euro III cars were compared with the model predictions for an average Euro III car, see Figure 23. For fuel consumption, CO and HC the accuracy of the simulation was high, but for NOx there was a systematic overestimation of emissions (Figure 25). The reasons for NOx overestimation are still not clear. But the very low absolute values have to be taken into consideration when looking at the deviation between measurements and model predictions.

![Figure 25: Simulation quality for the emission factors of the average Euro III petrol car in PHEM](image)

### 4.3.4 Software description

The PC part of PHEM forms part of the main software package, as described in Section 3.1. For the power and engine speed calculation, information about the vehicle is required, and this is specified in separate files - the vehicle data file, the full load curve, the engine map, the driving cycle and the dynamic correction (if available).
5 Summary, discussion and recommendations

TRL has been commissioned by the Highways Agency (HA) to assess the scientific understanding of ‘instantaneous’ emission models for road vehicles. This Report, which is the result of Task 1 of the project, has presented a review of existing models. The review explains the rationale of instantaneous emission modelling, and describes a number of models in some detail, with reference to aspects such as availability, cost, capabilities, ease of use and the robustness of the predictions. The findings of the review are briefly summarised in the following paragraphs, and some recommendations are provided for Task 2 of the project.

5.1 Summary and discussion

Instantaneous emission models aim to provide a precise description of vehicle emission behaviour by relating emission rates to vehicle operation during a series of short time steps (often one second). In principle, instantaneous models allow the user to calculate emissions for any vehicle operation profile, and therefore new emission factors can be generated without the need for further testing. The models inherently take into account the dynamics of driving cycles, and can therefore be used to explain some of the variability in emissions associated with given average speeds. Furthermore, instantaneous models allow emissions to be resolved spatially, and thus have the potential to lead to improvements in the prediction of air pollution. However, in order to apply instantaneous models detailed and precise measurements of vehicle operation and location are required, otherwise any potential benefits may be lost. This is likely to be rather difficult for many model users, as such information is relatively expensive to collect. As a consequence, the use of instantaneous models has mainly been restricted to the research community.

The complexity of instantaneous models has increased during the last 10-15 years. Some instantaneous models, especially the older models, relate fuel consumption and/or emissions to vehicle speed and acceleration during a driving cycle. Other models use some description of the engine power requirement. However, there are a number of fundamental problems associated with the development of instantaneous models. It is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and then it is not straightforward to allocate the emission values to the correct operating conditions. During measurement in the laboratory, an emission signal is dynamically delayed and smoothed, and this makes it difficult to align the emissions signal with the vehicle operating conditions. Until recently, such distortions have not been taken into account in instantaneous models. In the review the term ‘unadjusted’ has been used to refer to models in which no adjustments are made to the emission signals to account for dynamic distortion during measurement. Conversely, the term ‘adjusted’ has been used to describe models which do attempt to address the distortion. The models described in the review, grouped according to these distinctions, were:

Unadjusted models (speed, acceleration)  
- MODEM (original version)  
- MODEM (extended version)  
- DGV  

Unadjusted models (engine power)  
- PHEM (HDV part)  
- VeTESS  
- CHEM  

Adjusted models  
- EMPA model  
- PHEM (PC part)  

The basic characteristics of these models are summarised in Table 8. The Table provides details of, for example, the supplier of each model, the cost, and the coverage of the model in terms of vehicle categories and pollutants.
### Table 8: Model summary.

<table>
<thead>
<tr>
<th>Model</th>
<th>Original MODEM</th>
<th>Extended MODEM</th>
<th>DGV</th>
<th>PHEM (HDV)</th>
<th>VeTESS</th>
<th>CMEM</th>
<th>EMPA model</th>
<th>PHEM (PC)</th>
<th>ADVISOR</th>
<th>MOVES2004</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Developer/Supplier</strong></td>
<td>TRL, INRETS, TUV</td>
<td>TRL Limited</td>
<td>TUG</td>
<td>TUG</td>
<td>MRA/ VITO</td>
<td>University of California Riverside</td>
<td>EMPA</td>
<td>TUG</td>
<td>Originally developed by the US Department of Energy and the US National Renewable Energy Laboratory (NREL)</td>
<td>US EPA</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>£1,000 for research and £6,000 for commercial use&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Not commercially available</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not commercially available</td>
<td>ARTEMIS/COST 346: Source code 4000 €, input data 7000 €</td>
<td>Not ARTEMIS/COST 346: Source code 5000 €, input data 7000 €</td>
<td>5000 euro</td>
<td>Free</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Direct approach to TRL</td>
<td>Direct approach to TRL</td>
<td>Direct approach to TUG</td>
<td>Direct approach to TUG</td>
<td>Purchase from MIRA or VITO</td>
<td>Internet</td>
<td>Direct approach to EMPA</td>
<td>Direct approach to TUG</td>
<td>IVL</td>
<td>US EPA</td>
</tr>
<tr>
<td><strong>Vehicle Categories</strong></td>
<td>Petrol cars (pre-Euro 1, Euro I). Diesel cars (Euro I)</td>
<td>Petrol cars (pre-Euro 1, Euro I). Diesel cars (Euro I)</td>
<td>Petrol cars (pre-Euro 1, Euro I). Diesel cars (Euro I)</td>
<td>Rigid HGV (8 classes), artic. HGV (6 classes), coaches (2 classes), buses (3 classes). All vehicles pre-Euro 1 to Euro V.</td>
<td>Individual vehicles</td>
<td>Normal-emitting cars (12 classes), high-emitting cars (9 classes). HGV (9 classes). US classification.</td>
<td>Individual vehicles</td>
<td>Individual vehicles or average pre-Euro 1 to Euro IV diesel and petrol cars. Conventional vehicles, fuel cell and hybrid</td>
<td>Conventional vehicles, fuel cell and hybrid. Technologies include conventional internal combustion (all fuels), advanced internal combustion (gas and diesel), moderate hybrid-electric (gas and diesel), full hybrid-electric (gas and diesel) and dedicated electric.</td>
<td></td>
</tr>
<tr>
<td><strong>Pollutants</strong></td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, CO&lt;sub&gt;1&lt;/sub&gt;, PM, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, PM, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, CO&lt;sub&gt;1&lt;/sub&gt;, PM, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, CO&lt;sub&gt;1&lt;/sub&gt;, PM, (FC)</td>
<td>CO, HC, NO&lt;sub&gt;x&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt;, CO&lt;sub&gt;1&lt;/sub&gt;, PM, (FC)</td>
<td>Energy consumption, N&lt;sub&gt;2&lt;/sub&gt;O and CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td>v(t)</td>
<td>v(t)</td>
<td>v(t)</td>
<td>v(t), vehicle file, engine map, full-load curve, gradient</td>
<td>v(t), vehicle file, engine file</td>
<td>v(t), gradient, use of auxiliaries, soak time</td>
<td>v(t), vehicle-specific information</td>
<td>v(t), vehicle file, engine map, gradient</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td>E&lt;sub&gt;total&lt;/sub&gt;, E(t)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> The price for the original MODEM model was set by the project consortium at the time of its release (over 10 years ago).

<sup>b</sup> All costs relating to PHEM (HDV part and PC part) are provided by TUG, and are provisional. The price for the full set includes 20 hours consultancy. If the PHEM source code is bought, 8 hours training and a user manual are included (without travel costs).

<sup>c</sup> For a given vehicle category, v(t) = driving pattern (vehicle speed as a function of time).

<sup>d</sup> E<sub>total</sub> = total emissions over driving cycle. E(t) = emissions for each second of driving cycle.
Progress is clearly being made towards the accurate modelling of emissions from individual vehicles on a continuous basis, with an emphasis being placed on obtaining the ‘correct’ emission values at the exhaust pipe. However, in terms of their applicability instantaneous models still face a number of challenges. Firstly, as the effort required to model emissions from the newest vehicles on an instantaneous basis is increasing, the actual emission levels are decreasing. Given the cost of model development and application, this raises the question of whether instantaneous modelling is ultimately worthwhile. In addition, it is possible that the process of averaging over many vehicles to obtain representative emission estimates could obscure any improvements in accuracy associated with using a detailed model. Therefore, the possible advantages of instantaneous models need to be investigated in more detail, and this will be the main objective of Task 2 of the project.

5.2 Recommendations for Task 2

The actual predictions of the different models were not assessed as part of Task 1. In Task 2 of the project the performance of a number of different instantaneous models will be evaluated, relative to each other and to other types of model. In addition, their potential for improving the prediction of local air quality will also be examined.

The main recommendations for Task 2 are as follows:

- To select and assess the performance of a number of models. This will include, as a minimum, the DMRB, MODEM, and PHEM.

- A protocol for model evaluation should then be established. A series of vehicle operational profiles (driving cycles) should be defined for use as the input to the various models. The operational profiles should be stated in as much detail as possible, taking into account the different input data requirements of the models. A range of operational conditions ought to be reflected, and the cycles should include real-world driving cycles ranging from very-low-speed cycles which represent congested traffic conditions to high-speed cycles which represent motorway driving.

- Each driving cycle should be processed using all models, and emission factors should be determined for different vehicle categories. The outputs from the different instantaneous models should be compared. Comparisons should also be made between the outputs from the instantaneous models and the outputs from other available models.

- Continuous emission measurements from laboratory tests and on-board should be used to evaluate the performance of different instantaneous models. TRL possesses a large amount of data of this type, and this will be used appropriately. It will be important to take into account compatibility issues when comparing measurements and model predictions (e.g. measurements on individual vehicles compared with fleet predictions), as well as the different properties of the models.

- An air pollution prediction model could be ‘inverted’ to calculate the emission factors for different vehicle categories, based on ambient pollution measurements, and traffic data for a small number of roadside sites. The emission factors derived from the air pollution models could be compared with the emission factors from the emission models. This will require driving pattern measurements which correspond in time to the air pollution measurements. Air pollution measurements in road tunnels could also be in a similar way.
6 References


Unal A, Rouphail N M and Frey H C (2003). Effect of arterial signalization and level of service on


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

### Appendix A: Abbreviations and glossary of terms

**Table A1:** Abbreviations used in the Report.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADVISOR</td>
<td>Advanced vehicle simulator</td>
</tr>
<tr>
<td>ARTEMIS</td>
<td>Assessment and Reliability of Transport Emission Modelling and Inventory Systems(^{20})</td>
</tr>
<tr>
<td>CADC</td>
<td>Common ARTEMIS Driving Cycle</td>
</tr>
<tr>
<td>CMEM</td>
<td>Comprehensive Modal Emissions Model</td>
</tr>
<tr>
<td>CO</td>
<td>carbon monoxide</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>CVS</td>
<td>constant-volume sampler</td>
</tr>
<tr>
<td>COPERT</td>
<td>COmputer Program to calculate Emissions from Road Transport</td>
</tr>
<tr>
<td>DECADE</td>
<td>Development and Validation of a highly accurate emissions simulation tool capable of comparatively assessing vehicles operating under dynamic conditions</td>
</tr>
<tr>
<td>DMRB</td>
<td>Design Manual for Roads and Bridges</td>
</tr>
<tr>
<td>DGV</td>
<td>Digitised Graz Method</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse gases, Regulated Emissions, and Energy uses in Transportation model</td>
</tr>
<tr>
<td>HBEFA</td>
<td>Handbook of emission factors</td>
</tr>
<tr>
<td>HDV</td>
<td>heavy-duty vehicle</td>
</tr>
<tr>
<td>LDV</td>
<td>light-duty vehicle</td>
</tr>
<tr>
<td>MODEM</td>
<td>Modelling of emissions and fuel consumption in urban areas</td>
</tr>
<tr>
<td>MOVES</td>
<td>USEPA MOtor Vehicle Emission Simulator</td>
</tr>
<tr>
<td>NAEI</td>
<td>National Atmospheric Emissions Inventory (UK)</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>oxides of nitrogen</td>
</tr>
<tr>
<td>NO(_2)</td>
<td>nitrogen dioxide</td>
</tr>
<tr>
<td>OBD</td>
<td>on-board diagnostics</td>
</tr>
<tr>
<td>PERE</td>
<td>Physical Emission Rate Estimator.</td>
</tr>
<tr>
<td>PHEM</td>
<td>Passenger car and Heavy-duty Emission Model. One of the modelling tools developed under COST Action 346 and the ARTEMIS project</td>
</tr>
<tr>
<td>PM</td>
<td>particulate matter</td>
</tr>
<tr>
<td>RPA</td>
<td>relative positive acceleration</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective catalytic reduction</td>
</tr>
<tr>
<td>TEE</td>
<td>Traffic Energy and Emissions (model)</td>
</tr>
<tr>
<td>THC/HC</td>
<td>total hydrocarbons</td>
</tr>
<tr>
<td>UROPOL</td>
<td>Urban Road Pollution (model)</td>
</tr>
<tr>
<td>VERSIT+</td>
<td>VERkeers SITuatie Model</td>
</tr>
<tr>
<td>VeTESS</td>
<td>Vehicle Transient Emissions Simulation Software</td>
</tr>
<tr>
<td>VOCs</td>
<td>volatile organic compounds</td>
</tr>
</tbody>
</table>

\(^{20}\) European Commission 5th Framework project which will develop a harmonised emission model for road, rail, air and ship transport to provide consistent emission estimates at the national, international and regional levels. [http://www.trl.co.uk/artemis/introduction.htm](http://www.trl.co.uk/artemis/introduction.htm)
Table A2: Glossary of terms used in the Report.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driving cycle</strong></td>
<td>In this Report the term ‘driving 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. The driving cycle may be based upon real-world measurements, or may take the form of an ‘idealised’ schedule of vehicle operation.</td>
</tr>
<tr>
<td><strong>Driving pattern</strong></td>
<td>Here, the term ‘driving pattern’ is used to describe how a vehicle is to be 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 Report it has been assumed that a driving pattern only becomes a driving cycle once it has been used directly in the measurement of emissions.</td>
</tr>
<tr>
<td><strong>Dynamics</strong></td>
<td>Variables which emission modellers use to describe the extent of transient operation 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.</td>
</tr>
<tr>
<td><strong>Road characteristics</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Traffic characteristics/conditions</strong></td>
<td>Information relating to the bulk properties of the traffic stream – principally its speed, composition and volume/flow or density.</td>
</tr>
<tr>
<td><strong>Transient</strong></td>
<td>Relates to when the operation of a vehicle is continuously varying, as opposed to being in a steady state.</td>
</tr>
<tr>
<td><strong>Vehicle operation</strong></td>
<td>The way in which a vehicle is operated (e.g. vehicle speed, throttle position, engine speed, and gear selection).</td>
</tr>
</tbody>
</table>
TRL was commissioned by the Highways Agency to assess the scientific understanding of ‘instantaneous’ emission models for road vehicles. The overall aims of the research were to review and evaluate instantaneous emission data and models, and to show how improvements in modelling could lead to improvements in the prediction and control of local air quality. This review explains the rationale of instantaneous ‘hot’ emission modelling, and describes a number of models in some detail, with reference to aspects such as availability, cost, capabilities, ease of use and the robustness of the predictions. This review covers emission models which have been available for some time (e.g. MODEM, DGV, ADVISOR, MOVES), as well as those from recent and on-going research programmes (e.g. PHEM, VeTESS, CMEM).