Scoping study on the potential for instantaneous emission modelling: summary report

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

PPR 270

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Executive summary

This Report summarises a research project in which the scientific understanding of ‘instantaneous’ emission models for road vehicles was assessed. 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 theory, the advantages of instantaneous emission models include the following:

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

However, in order to apply instantaneous emission models, detailed and precise information on vehicle operation and location is required, otherwise any potential benefits may be lost. Obtaining such information is likely to be rather difficult for many model users as it is relatively expensive to collect. One potential solution involves the use of micro-simulation traffic models to generate the required emission model inputs. Furthermore, 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. The potential advantages of instantaneous models therefore needed to be investigated in more detail.

The overall aims of this project 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. The project was 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, microsimulation traffic models and air pollution models.
- Task 4: Summary and recommendations for model development and future research.

This Report (Task 4) summarises the work conducted on Tasks 1 to 3. The Report concludes that the instantaneous emission models PHEM and MODEM are equally good at predicting estimation from light-duty vehicles over a trip, even though MODEM is older than PHEM, uses assumptions for Euro III and Euro IV vehicles rather than measurements, and includes no adjustment for the distortion of the emission signal during measurement. The model adjustment process may offer benefits where the emissions over very short time periods or the identification of peaks (hot-spots) are required. Over an entire trip, the smoothing of the emission measurements is less critical. For light-duty emissions over an entire level route, a MODEM-type model may therefore be suitable. However, for emissions over very short sections (e.g. for spatial allocation of emissions), over inclines or carrying varying load, then a PHEM type model is more appropriate.

Another conclusions was that one of the main challenges in micro-scale model integration is the matching of the different vehicle types defined in the traffic simulation and emissions components. The systems of vehicle classification required for emission models are generally more complex than those used in traffic models. Ideally, the aim would be to link the most detailed and up-to-date instantaneous emission model to the most appropriate traffic model. The best candidate for the emission model is probably PHEM. However, PHEM is itself rather time consuming to run, and would probably have to be run ‘off-line’. Information on vehicle load and gradient would need to be obtained from sources other than the traffic models.

The links between instantaneous emissions and air pollution dispersion modelling tools remain largely untested.

The report provides recommendations and a draft specification for the development of a new instantaneous emission model.
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1 Introduction

A range of pollutants are emitted from road vehicles as a result of combustion and other processes. Exhaust emissions of carbon monoxide (CO), volatile organic compounds (VOCs), oxides of nitrogen (NOx) 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 (CO2), methane (CH4) and nitrous oxide (N2O). However, with the exception of CO2, unregulated pollutants have been characterised in less detail than the regulated pollutants. Emission levels are dependent upon many parameters, including vehicle-related factors such as make, model, size, fuel type, technology level and mileage, and operational factors such as speed, acceleration, gear selection, road gradient and ambient temperature.

All emission models for road vehicles must take into account the various factors affecting emissions, although the manner and detail in which they do so can differ substantially (Boulter et al., 2006). ‘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 theory, the advantages of instantaneous emission models include the following:

- Emissions can be calculated for any vehicle operating profile specified by the model user, and thus new emission factors can be generated without the need for further testing.
- Instantaneous models inherently take into account the dynamics of driving patterns, and can therefore be used to explain some of the variability in emissions associated with given average speeds.
- Instantaneous models allow emissions to be resolved spatially, and could thus lead to improvements in the prediction of air pollution. Air quality models typically assume that emissions are evenly distributed along a road section. It is therefore likely that such models will under-predict emissions and the resulting ambient concentrations at some locations, such as in the vicinity of junctions (Tate et al., 2005).

However, in order to apply instantaneous emission models detailed and precise information on vehicle operation and location is required, otherwise any potential benefits may be lost. Obtaining such information is likely to be rather difficult for many model users as it is relatively expensive to collect. One potential solution involves the use of micro-simulation traffic models to generate the required emission model inputs. Furthermore, 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. The potential advantages of instantaneous models therefore needed to be investigated in more detail.

TRL was 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 this project 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. The project was 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, microsimulation traffic models and air pollution models.
- Task 4: Summary and recommendations for model development and future research.

A separate Report was compiled for each Task. For Task 1, several instantaneous emission models were described in detail by Boulter et al. (2006). The results of Task 2 were presented by Barlow et al. (2007), and Task 3 was addressed by Boulter and McCrae (2006). This Report (Task 4) summarises the work conducted on Tasks 1 to 3 (Chapters 2 to 4), and provides recommendations for the development of a new model. Appendix A provides a list of abbreviations and a glossary which explains the terms used in the Report. A draft specification for the development of a new instantaneous emission model is given in Appendix B.
2  Review of existing models

Boulter et al. (2006) explained the rationale of instantaneous emission modelling, and described several models with reference to aspects such as availability, cost, capabilities, ease of use and the robustness of the predictions. The review dealt principally with ‘hot’ exhaust emissions, as most of the research relates to this topic.

The complexity of instantaneous models has increased during the last 10 to 15 years. Some models relate fuel consumption and/or emissions to vehicle speed and acceleration during a driving cycle. Other models use a description of the engine power requirement. However, there are a number of 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 delayed and smoothed, and this makes it difficult to align the signal with the vehicle operating conditions. Until recently, such distortions had not been taken into account in models. Boulter et al. (2006) employed the term ‘unadjusted’ to refer to models in which no adjustments are made to the emission signals to account for distortion during measurement. Conversely, the term ‘adjusted’ was 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 based on speed and acceleration
- MODEM (original version)
- MODEM (extended version)
- DGV

Unadjusted models based on engine power
- PHEM (heavy-duty vehicle part)
- VeTESS
- CMEM

Adjusted models
- EMPA model
- PHEM (passenger car part)

a MODEM = modelling of emissions and consumption in urban areas (Jost et al., 1992; Joumard et al., 1995).
b Barlow (1997).
c DGV = Digitised Graz model (Sturm et al., 1994).
d PHEM = passenger car and heavy-duty mission model (Rexeis et al., 2005).
e VeTESS = vehicle transient emissions simulation software (Pelkmans et al., 2004).
f CMEM = comprehensive modal emissions model (Barth et al., 2001).
g Atjay et al. (2005).

The basic characteristics of these models are summarised in Table 1, including details of the supplier of each model, the cost, and the coverage of the model in terms of vehicle categories and pollutants. The actual predictions of the different models were not assessed as part of Task 1 – this work was undertaken in Task 2. The main recommendations for Task 2 from the review were as follows:

- A number of models (instantaneous an other types of model) should be selected, and a protocol for model evaluation should be established.
- A series of real-world vehicle operating profiles (driving patterns) should be defined for use as the input to the various models.
- Each driving pattern should be processed using all models, and emission factors should be determined for different vehicle categories. The outputs from the different models should be compared.
- Comparisons should also be made between the emission factors predicted using the various models.
- Continuous emission measurements from laboratory and on-board tests should be used to evaluate the performance of different instantaneous models.
- An air pollution prediction model should be ‘inverted’ to calculate the emission factors for different vehicle categories, based on ambient pollution and traffic data for a small number of sites. The emission factors derived from the air pollution models should be compared with the model predictions. Air pollution measurements in road tunnels could also be used in a similar way.

1 Emissions produced when the engine and catalyst are at their full operational temperatures.
Table 1: Summary of instantaneous emission models (Boulter et al., 2006).

<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>
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<td><strong>Developer/ Supplier</strong></td>
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<td>TUG</td>
<td>TUG</td>
<td>MRA/ VITO</td>
<td>University of California Riverside</td>
<td>EMPA</td>
<td>TUG</td>
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<td><strong>Cost</strong></td>
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<td>ARTEMIS/COST 346$^b$; Source code free, input data 3,000 €. Non-ARTEMIS/COST 346: Source code 5,000 €, input data 7,000 €.</td>
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<td>US$20</td>
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<td><strong>Inputs$^c$</strong></td>
<td>$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)$, vehicle file, engine map, gradient</td>
<td></td>
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<tr>
<td><strong>Outputs$^d$</strong></td>
<td>$E_{total}, E(t)$</td>
<td>$E_{total}, E(t)$</td>
<td>$E_{total}, E(t)$</td>
<td>$E_{total}, E(t)$</td>
<td>$E_{total}, E(t)$</td>
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<td>$E_{total}, E(t)$</td>
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$a$ The price for the original MODEM model was set by the project consortium at the time of its release (over 10 years ago).

$b$ 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).

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

$d$ $E_{total}$ = total emissions over driving cycle. $E(t)$ = emissions for each second of driving cycle.


3 Model evaluation

Barlow et al. (2007) described the model evaluation phase of the work. The main stages in the evaluation process were as follows:

- Stage 1: Selection of models and required output.
- Stage 2: Definition of driving patterns (i.e. model input).
- Stage 3: Model execution and comparison.
- Stage 4: Evaluation of model accuracy.

3.1 Model selection and definition of driving patterns

Each model in Table 1 was taken in turn, and the arguments for and against inclusion in the evaluation exercise were considered. The original MODEM model has been superseded by the extended version. Similarly, the DGV model has been effectively superseded by PHEM. The VeTESS model considers only one vehicle at a time, and is not particularly well suited to generating emission factors. In order to use CMEM in Europe, a correspondence between the US emission standards and EU emission standards must be established, a process which is not straightforward for a number of reasons, and the EMPA model remains more a concept than a tool for predicting emission factors. These models could not therefore be included in the main evaluation. The only instantaneous models which were considered to be appropriate for inclusion were the extended version of MODEM and PHEM (HDV and PC parts). However, several other types of model were included. These models were:

- NAEI - Average speed (AS) model
- COPERT III - Average speed (AS) model (Ntziachristos and Samaras, 2000)
- ARTEMIS (v3b) - Average speed (AS) model
- ARTEMIS (v3b) - Traffic situation (AS) model
- HBEFA (v2.1) - Traffic situation (TS) model (INFRAS, 2004)
- VERSIT+ - Multiple linear regression (MLR) model (Smit et al., 2005)

The second stage of the evaluation process involved the definition of a series of vehicle operating profiles (driving patterns) to be used as the input to the various models. This was based on a large TRL has database of real-world driving patterns which had been collected using instrumented vehicles as part of several research projects.

3.2 Model comparison

Each driving pattern was processed using all the models included in the evaluation, and emission factors were determined for the specified vehicle categories. The outputs from the different models were then compared - on the basis of a number of statistical parameters - with the emission factors currently used in the NAEI.

Generally, there was a very good agreement between the shapes of the speed-emission curves in the NAEI and those of the various models tested. The ARTEMIS models (both traffic situation and average speed) and PHEM gave different shaped curves for CO and HC emissions from petrol cars, whilst the ARTEMIS traffic situation model curves for NO\textsubscript{x} also differed for petrol cars. COPERT produced different shaped curves for NO\textsubscript{x} emissions from diesel cars, HGVs and buses. VERSIT has different trends for CO, HC and NO\textsubscript{x} from petrol cars, NO\textsubscript{x} and PM from diesel cars and CO\textsubscript{2} from both.

With regards the magnitude of the emissions estimates, the best agreements between the models appeared to be for NO\textsubscript{x} and CO\textsubscript{2}. For CO and HC, most of the comparisons appeared to show poor agreement, whilst for PM there were both good and poor agreements depending on the vehicle category and pollutant.

3.3 Evaluation of model accuracy

Four types of assessment were applied in an attempt to determine the accuracy of the PHEM and MODEM predictions:
• Comparisons with laboratory measurements.
• Comparisons with on-board measurements.
• Comparisons with the results from the inversion of an air pollution model.
• Comparisons with the results from measurements in the Hatfield tunnel.

CMEM was therefore not included in the main assessment. Instead, a provisional evaluation was conducted separately.

**Comparisons with laboratory measurements**

The emissions profiles predicted using PHEM and MODEM were compared with those measured in previous TRL emission test programmes. A statistical evaluation procedure was applied. The criteria which were evaluated included the absolute difference in total emissions, the differences in the shape of the emission profile, and the difference in the ‘typical’ emissions which occur for the most part of the driving cycle.

Although some values were under-estimated, the majority of the results were over-estimated by both MODEM and PHEM. In all cases, both MODEM and PHEM gave estimates of CO\textsubscript{2} and fuel consumption which were close to the measurements – in most cases CO\textsubscript{2} was within 20% of the measured values.

For Euro I cars, MODEM gave better results for CO, HC and NO\textsubscript{x}. However, for Euro III cars PHEM produced the closer estimates, especially for Euro III diesel cars.

For heavy-duty vehicles, PHEM gave results very close to the measured values, with the majority of the estimated values being within 30% of the measured results.

Both PHEM and MODEM had similar relative root mean square (RMS) errors (i.e. errors in the shapes of the curves) for the different vehicle types – in some cases PHEM was slightly better, and in other cases MODEM. It was therefore difficult to differentiate between their accuracy. In all cases, CO\textsubscript{2} and fuel consumption were modelled very accurately. For cars, HC estimates appeared to be the most error prone, though CO emissions from Euro III cars also had a very high RMS error.

For heavy-duty vehicles, all of the emission predictions appeared to be close, with the largest relative RMS errors occurring with CO and HC – though all of these errors were within 1%.

**Comparisons with on-board measurements**

The predictions obtained using PHEM and MODEM were also compared with on-board exhaust emission measurements for a Euro III petrol car. As with the chassis dynamometer results, there was a very good agreement with the on-board CO\textsubscript{2} and fuel consumption data for both PHEM and MODEM. For the other pollutants, the models generally over-estimated emissions – the main exception being HC predicted by PHEM which was very close to the measured values.

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

The air pollution prediction algorithms in the DMRB screening Method were inverted to estimate emission factors for vehicles on Marylebone Road, London. The calculation was conducted using air pollution data from 2004, with the roadside contribution from the traffic being determined from the difference between the concentration at the Marylebone Road and the concentration at a background site at Bloomsbury. Based on the total traffic flow\textsuperscript{2}, an average vehicle emission factor was also calculated. Separate emission factors (CO, NO\textsubscript{x}, PM\textsubscript{2.5}) for LDVs and HDVs were then calculated using multiple regression analysis. Driving patterns recorded on Marylebone Road in 2003 were used as input to MODEM and PHEM, and the average speeds were used in the other models (apart from HBEFA, for which a traffic situation description was used).

In the case of LDVs, the DMRB inversion gave emission factors for CO, NO\textsubscript{x} and PM\textsubscript{2.5} of 7.0, 1.0 and 0.04 g vehicle\textsuperscript{-1} km\textsuperscript{-1} respectively. For HDVs, the emission factors for CO, NO\textsubscript{x} and PM\textsubscript{2.5} were 1.8, 7.0 and 0.25 g vehicle\textsuperscript{-1} km\textsuperscript{-1} respectively. However, the emission factors obtained by inversion of the DMRB were substantially higher than the predicted emission factors, although for PM the inverse model gave an emission factor which was reasonably close to the emission factor predicted using the NAEI method. It was considered unlikely that the predictions of the different emission models were systematically wrong. Rather, there are a

\textsuperscript{2} Motorcycles were excluded from this calculation, as they only form a small proportion of the traffic.
number of errors associated with the inverse modelling approach itself, and further testing and refinement is required before this can be viewed as a reliable means of testing the accuracy of emission models

**Comparisons with the results from measurements in the Hatfield tunnel**

Air pollution measurement campaigns were conducted by TRL in the Hatfield Tunnel in late 2005 and early 2006. Continuous measurements were undertaken of NO, NO$_2$ and O$_3$ at three locations within the tunnel: (i) close to the tunnel entrance, (ii) close to the tunnel mid-point and (iii) close to the tunnel exit. Meteorological conditions and traffic characteristics were also recorded. The differences between the hourly mean NO$_x$ concentrations at the tunnel exit and tunnel entrance were used to determine average fleet-weighted NO$_x$ emission factors. NO$_x$ emission factors for different vehicle categories were again estimated using multiple regression analysis. A single car (petrol, Euro III) was equipped for the measurement of driving patterns, according to the needs of the instantaneous models. This vehicle was driven repeatedly through the tunnel at different times of day; a total of 36 driving patterns were recorded in the tunnel. The driving patterns recorded using the instrumented vehicle were used as direct input for MODEM and PHEM(PC). As in the inverse modelling exercise, the average speed of the driving patterns were used in the other models (apart from HBEFA, for which a traffic situation description was used).

From the tunnel measurements, the estimated NO$_x$ emission factors for HGVs (3-4 g vehicle$^{-1}$ km$^{-1}$) were much higher than that for cars and small vans (0.18 g vehicle$^{-1}$ km$^{-1}$). However, the predicted NO$_x$ emission factors were all much higher than the emission factor derived from the statistical analysis of the Hatfield tunnel data. It could not be stated conclusively that either PHEM or MODEM offered any advantages over the other models.

**Evaluation of CMEM**

CMEM was run for a number of vehicle categories over three TRL/WSL cycles (urban, suburban/rural and motorway). The resulting emissions were compared with data measured from five Euro I medium sized petrol cars. The CMEM emissions were also compared with the emissions calculated by PHEM for various Euro standards (Euro I-IV). In addition, emissions were calculated with CMEM for a modified vehicle category to evaluate the effect of changing the vehicle specifications from a typical US vehicle to a more European one.

CMEM appeared to be capable of producing reasonable emission estimates for Euro I vehicles. However, there are a number of limitations to its use. One major limitation is the lack of Euro specification data. It is quite simple to add vehicle specifications for European cars, but this does not change the emission factors associated with the various vehicle categories. It may be possible to add additional vehicle categories with corresponding emission data, but this is not a simple task. There are also no emission factors for diesel vehicles in CMEM.

Another limitation is the use of a fixed overall gear ratio (the ‘S’ parameter – revs per mph). The selection of an appropriate value for this parameter seems to be critical – it has a very large effect on the resulting emissions. This makes the model less adaptable to different conditions. For low-speed urban driving patterns, a higher value of ‘S’ is needed, and for high-speed motorway driving patterns a lower value is required, to allow for the different gear usage. It might be possible to pre-process each driving pattern to pick a suitable value for ‘S’ but this complicates the processing and it might require complex driving patterns (i.e. those containing both high-speed and low-speed sections) to be split up into various parts.
4 Links with micro-scale traffic and air pollution models

4.1 Linking micro-simulation traffic and emission models

One of the drawbacks of instantaneous emission models is the requirement for detailed input data on vehicle operation to be specified by the user. Few users have the information required, and one potential solution to this is the use of traffic models, in particular micro-simulation models, to generate the required inputs. However, the application of a micro-simulation traffic model to a particular part of the road network is a time-consuming process which requires some form of calibration.

An essential property of all micro-simulation traffic models is the prediction of the operation of individual vehicles in real time, over a series of short time intervals, and using models of driver behaviour such as car-following, gap acceptance, lane-changing and signal behaviour theories, rather than aggregate relationships. The three traffic micro-simulation models described in this Report – VISSIM, PARAMICS and DRACULA – are the best-known in the UK. It is clear that all three traffic micro-simulation models are very detailed, but they do appear to have similar characteristics.

The calculation of emissions is relatively straightforward, once a suitable model has been identified and a correspondence has been established between the traffic model outputs and the emission model requirements. Of the three models, VISSIM appears to have the most sophisticated and up-to-date in-built emission module. However, even this is now several years old. However, the three traffic models have been linked with external emission models in a number of different studies. VISSIM has been linked to MODEM, and more recently all three traffic models have been linked to CMEM. Although the links with CMEM appear to represent the state of the art, there must be some doubts about the applicability of CMEM in the UK.

The output parameters from micro-simulation traffic models were compared with the input parameters required for emission modelling. The most important factors in relation to the estimation of vehicle emissions (in general) are the road characteristics, the traffic flow, the vehicle operation (e.g. vehicle speed, gear, engine load) and the system of vehicle classification. Road characteristic parameters are not always defined in micro-simulation traffic models, but this is not a major drawback as these are not generally required for micro-simulation emission modelling, and in any case they can generally be otherwise obtained by the model user. The road segment length is an important parameter in any model which is used for estimating emissions, and this is included in all traffic models. One of the most important factors is the road gradient, which has a large effect on emissions from heavy-duty vehicles, and should be taken into consideration. For emission modelling purposes, the total number of vehicles per specified period is required. As this type of information is fundamental to micro-simulation, this aspect of model integration is unlikely to present any difficulties. Traffic density is also used in the traffic situation modelling approach to define vehicle operation, but this parameter is not needed in instantaneous emission models as the driving pattern must be specified anyway. Vehicle operation is one of the crucial considerations when integrating traffic and emission models. For the sake of emissions accuracy it is crucial to take into account the kinematics (the driving pattern) and the power demand. Another important parameter, especially for HDVs, is the vehicle load. In the case of micro-scale modelling, there is a reasonably close correspondence between the outputs of the traffic models (speed as a function of time and location) and the input requirements of emission models. However, information on vehicle loads will need to be obtained from sources other than the traffic models.

One of the main challenges in micro-scale model integration is the matching of the different vehicle types defined in the traffic simulation and emissions components. The systems of vehicle classification required for emission models are generally more complex than those used in traffic models. In emission models, hundreds of different vehicle categories are required to take account of the various factors affecting emissions. Traffic models typically have different vehicle types that are based on how they operate within a roadway network. In addition to the obvious divisions of vehicle types (i.e. motorcycles, passenger cars, buses, HGVs), categories are often made based on vehicle performance (e.g. high-performance cars, low-performance cars) that can be closely related to traffic simulation parameters. In the case of HGVs, transportation models typically categorise vehicles based on their configuration and number of axles. In all cases, a straightforward approach to handling the vehicle matching is to create an appropriate mapping between the vehicle types defined in the traffic simulation model, and the vehicle types defined in the emission model (Barth et al., 2001). From an
emissions perspective, vehicles can be therefore separated into ‘coarse’ categories (e.g. cars, LGVs, buses, HGVs, motorcycles), for which it might be possible to obtain correspondence with traffic models, and ‘detailed’ categories (e.g. categories of emission legislation, weight, engine capacity) which relate to emission legislation and would not be expected outputs from traffic models. Neither MODEM nor PHEM cover direct-injection petrol cars, cars using fuels other than petrol or diesel, light commercial vehicles (M, N1), or motorcycles.

In CMEM the categories are based on vehicle types and emission standards which are relevant to the US. For example, CMEM has 26 different categories of light-duty vehicle. The basic car categories are ‘no catalyst’, ‘2-way (oxidation) catalyst’, ‘three-way catalyst’, and ‘Tier 1’. There are also specific categories which relate to high-emitting vehicles. In order to use CMEM in Europe, a correspondence between the US emission standards and EU emission standards must therefore be established, a process which is not straightforward for a number of reasons. For example, the US and EU emission standards have different values, were introduced in different years and based on different test cycles. Even where a correspondence can be obtained between the US and EU emission standards, there is no guarantee that real-world (off-cycle) emissions will be equivalent for the corresponding US and EU vehicles, given the different vehicle design standards, possible differences in the operation of fuelling and emission control systems, and differences in vehicle operation. Furthermore, it should be noted that in the US standards a system of ranges, and the emission limit value refers to an average value for each manufacturer. This implies that a car manufacturer can produce models with quite different emission characteristics. For these reasons, the use of CMEM in Europe cannot be recommended, despite the fact that some attempts have been made to do so.

Ideally, the aim would be to link the most detailed and up-to-date instantaneous emission model to the most appropriate traffic model. The best candidate for the emission model is probably PHEM. However, PHEM is itself rather time consuming to run. It is likely that were PHEM to be fully integrated into a micro-simulation traffic model, then the speed of the model would be reduced considerably. It is likely that the better option would be to run PHEM ‘off-line’.

4.2 Links between emission and air pollution models

Air pollution models can be simple empirical tools, or more sophisticated and complex tools based upon first principles and incorporating extensive input data. For road transport applications, the input requirements can again be relatively simple, such as data on traffic flows and speeds, and the use of default parameters to characterise the dispersion process. Alternatively, dispersion modelling tools which incorporate computational fluid dynamics (CFD) and chemical transformation schemes can require complex and comprehensive input data.

CFD modelling, which had been restricted by its computer processing requirements, is now widely used in air pollution assessments. However, whilst CFD tools routinely incorporate complex air flow regimes, the integration of instantaneous emissions from road transport sources has not been developed. Indeed, those projects that have employed micro-simulation traffic and emission modelling have routinely employed time-averaged emission factors for subsequent use in dispersion modelling processes.

Instantaneous emission models can be used to predict both cycle average emissions and emissions on a continuous basis (normally every second of a driving cycle). Cycle average emissions - normally derived using average speed models - are currently used in most air pollution prediction models. However, with emission factors of this type it is not possible to ‘map’ emissions with a high spatial resolution.

For this to be possible, there is a need to understand the links between the outputs of instantaneous emission models and the input requirements of the detailed types of air pollution model which permit mapping. However, the link between instantaneous emissions and air pollution dispersion modelling tools remains largely untested. With respect to CFD model operation for finer spatial and temporal resolution calculations, there would of course be longer calculation times required.
5 Conclusions and recommendations for model development

5.1 Conclusions

The main conclusions from this project are presented below.

(i) Progress is clearly being made towards the accurate modelling of emissions from individual vehicles on an instantaneous basis, with an emphasis on obtaining the ‘correct’ emission values at the exhaust pipe.

(ii) In practice, the only instantaneous models which are currently available for the estimation of emission factors are MODEM, CMEM and PHEM. Of these, the model which is most relevant to modern European vehicles is PHEM.

(iii) PHEM and MODEM are equally good at predicting estimation from light-duty vehicles over a trip, even though MODEM is older than PHEM, uses assumptions for Euro III and Euro IV vehicles rather than measurements, and includes no adjustment for the distortion of the emission signal during measurement.

(iv) The model adjustment process may offer benefits where the emissions over very short time periods or the identification of peaks (hot-spots) are required. Over an entire trip, the smoothing of the emissions is less critical.

(v) The emissions factors in MODEM require updating for newer vehicle types. In addition, there is no version available for heavy-duty vehicles.

(vi) Whereas MODEM produces emissions for typical vehicles over a level route, both PHEM and CMEM allow emissions to be calculated for an individual vehicle. The load carried by the vehicle and the road gradient can be taken into account. Therefore, PHEM and CMEM offer much more flexibility, although they require more detailed input data.

(vii) Although CMEM produced reasonable results for Euro I vehicles, it does not contain emission factors for modern European cars. To be useful, revised emission factors would have to be generated and incorporated within the model. Another shortcoming with the model is the use of a fixed gear ratio. The selection of this parameter heavily influences the resulting emissions.

(viii) For light-duty emissions over an entire level route, a MODEM type model may be suitable. However, for emissions over very short sections (e.g. for spatial allocation of emissions), over inclines or carrying varying load, then a PHEM type model is more appropriate.

(ix) In order to apply instantaneous emission models detailed and precise information on vehicle operation and location is required, otherwise any potential benefits may be lost. Obtaining such information is likely to be rather difficult for many model users as it is relatively expensive to collect. One potential solution involves the use of micro-simulation traffic models to generate the required emission model inputs. Furthermore, 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. On a regional network level the additional benefits of emission micro-simulation are marginal. However at the local level, their use in the assessment of pollution hot spots could offer a range of distinct advantages.

(x) The three traffic micro-simulation models focussed on in this study – VISSIM, PARAMICS and DRACULA – are the best-known in the UK. The three traffic models have been linked with external emission models in a number of different studies. VISSIM has been linked to MODEM, and more recently all three traffic models have been linked to CMEM. Although the links with CMEM appear to represent the state of the art, there must be some doubts about the applicability of CMEM in the UK.

(xi) There is a reasonably close correspondence between the outputs of the traffic models (speed as a function of time and location) and the input requirements of emission models. One of the main challenges in micro-scale model integration is the matching of the different vehicle types defined in the traffic simulation and emissions components. The systems of vehicle classification required for emission models are generally more complex than those used in traffic models. Information on vehicle
Ideally, the aim would be to link the most detailed and up-to-date instantaneous emission model to the most appropriate traffic model. The best candidate for the emission model is probably PHEM. However, PHEM is itself rather time consuming to run. It is likely that were PHEM to be fully integrated into a micro-simulation traffic model, then the speed of the model would be reduced considerably. It is likely that the better option would be to run PHEM ‘off-line’.

The links between instantaneous emissions and air pollution dispersion modelling tools remain largely untested.

5.2 Recommendations

Some recommendations for further model development are provided below, and more details are given in the specification in Appendix B.

Overview

A new instantaneous emission model could improve the exhaust emission estimates for certain traffic conditions, and the development of such a model should be investigated. The following aspects should be considered in the model development:

(i) The model would need to be designed in such a way that it is capable of accepting the output from a micro-simulation traffic model and allowing the results to be used as input into an air pollution model. As both traffic and air pollution micro-simulations usually take several hours to run, the emission model would be designed principally for off-line use. However, the possibility of full integration with the most common traffic micro-simulation models in the UK (VISSIM, PARAMICS and DRACULA) and the HA dedicated model SISTM, should also be investigated.

(ii) Further consideration should be given to the assessment of the relative performance of the traffic micro-simulation models VISSIM, PARAMICS, DRACULA and SISTM. This should include an assessment of the model-derived driving characteristics with those recorded through real-world measurements from instrumented vehicles.

(iii) The emission model should be adaptable, so that various traffic model input files can be used (different models, different units, different frequencies, etc).

(iv) The model should also allow output files of various formats to be produced, which could be used as input into air pollution models.

Basis for model development

The main options for developing a new instantaneous emission model are as follows:

(i) A new model could be developed ‘from scratch’. This would involve a large and very expensive measurement programme (several million pounds), involving tests on different vehicle types and using different driving cycles, followed by an extensive period of data analysis, model construction and documentation. This is not a viable proposition.

(ii) A licence to further develop or adapt an existing model (e.g. CMEM, PHEM) could be obtained from the original developer. Given that the measurements underpinning such models have generally been conducted to address the model design requirements, adding or replacing data is not likely to be a straightforward process.

(iii) The developers of existing models could be asked to adapt the models for a particular set of requirements which relate to the UK situation.

(iv) An existing model could be run to generate data which could then be used to develop a new model. However, the use of one model to develop another would inevitably lead to greater uncertainty in the model output. Furthermore, if the original model is based upon simple speed and acceleration matrices (such as MODEM), then this would be possible. However, if is it a more sophisticated vehicle dynamics
model (such as PHEM), then this would be much more complicated.

**Vehicle categorisation**

Traffic models use a limited number of vehicle categories (cars, LGVs, HGVs, buses, 2-wheel vehicles). For the estimation of emissions, these categories will need to be sub-divided by Euro standard and weight or engine size. There are various ways that the emissions module could handle these additional categories, including:

(i) For each vehicle in the traffic model output, evaluate the emissions for each sub-category (e.g. for cars: evaluate small, medium, large cars; petrol and diesel; pre-Euro I to V) and derive a fleet-weighted average. However, this would require a lot of data processing.

(ii) Count how many vehicles are in the traffic output data, and assign each one an appropriate sub-category. This means that the emissions are only evaluated once. However, if the vehicle count is small, it will be difficult to achieve the correct fleet composition. This may also affect the spatial & temporal results in comparison to using averaged vehicles. It is more realistic however.

**Intermediate data processing**

The traffic models can generate extremely large output files (a gigabyte or more). To allow the module to be used on PCs of various specifications (rather than limiting its use to powerful work stations), the traffic files may need to split up into numerous temporary files – e.g. one file for each vehicle. Due to limitations in the number of files that can be open at one time, this data processing may need to be carried out in a number of stages.
6 References


Tate, J E, Bell M C and Liu R (2005). The application of an integrated traffic micro-simulation and instantaneous emission model to study the temporal and spatial variations in vehicular emissions at the local-scale. Proceedings of 14th International Conference, Transport and Air Pollution, Graz, 2005 Heft 85/1, pp. 138-147.
# Appendix A: Abbreviations and glossary of terms

Table A1: Abbreviations used in the Report.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARTEMIS</td>
<td>Assessment and Reliability of Transport Emission Modelling and Inventory Systems(^3)</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>DMRB</td>
<td>Design Manual for Roads and Bridges</td>
</tr>
<tr>
<td>DGV</td>
<td>Digitised Graz Method</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>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>PHEM</td>
<td>Passenger car and Heavy-duty Emission Model. One of the emission models derived from COST Action 346 and the ARTEMIS project</td>
</tr>
<tr>
<td>PM</td>
<td>particulate matter</td>
</tr>
<tr>
<td>THC/HC</td>
<td>total hydrocarbons</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>

\(^3\) European Commission 5\(^{th}\) 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
Table A2: Glossary of terms used in the Report.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving cycle</td>
<td>In this Report the term ‘driving cycle’ is used to describe how a vehicle is to be operated <em>during a laboratory emission test</em>. 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>Driving pattern</td>
<td>Here, the term ‘driving pattern’ is used to describe how a vehicle is to be operated <em>under real-world conditions, based on direct measurement</em>, 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>Dynamics</td>
<td>Variables which emission modellers use to describe the extent of transient operation in a driving cycle (<em>e.g.</em> 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>Road characteristics</td>
<td>Information relating to the road, such as the geographical location (<em>e.g.</em> urban, rural), the functional type (<em>e.g.</em> distributor, local access), the speed limit, the number of lanes and the presence or otherwise of traffic management measures.</td>
</tr>
<tr>
<td>Traffic characteristics/conditions</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>Transient</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>Vehicle operation</td>
<td>The way in which a vehicle is operated (<em>e.g.</em> vehicle speed, throttle position, engine speed, gear selection).</td>
</tr>
</tbody>
</table>
Appendix B: Draft specification for the development of an instantaneous emission model

B1 Aims

The primary aim is to develop a tool that may be used to estimate emissions associated with unusual traffic and topographic conditions. That is to say, those conditions where the existing average speed emission factors may not be sensitive enough to the local conditions. This will be achieved by developing an emissions module that can be incorporated within a traffic module or that can post-process the speed traces produced by the traffic model to predict the emissions along links or sub-sections of links.

The developed emissions module should consist of a series of lookup tables, generated from the PHEM emissions model. When a speed (km/h) and an acceleration (m/s\(^2\)) are input into the module, the output will be an array of emissions in g per time period.

![Figure B1: Basic schematic of the emissions model.](image)

Due to the different speeds and accelerations of light-duty and heavy-duty vehicles, the speed/acceleration input will need to be classified into different groups. This is likely to be a coarse classification of simply light-duty and heavy-duty vehicles, although the module should be adaptable if a more detailed classification is available.

An alternative input might be to enter two speeds and the time period – the module is then able to calculate the average speed and acceleration from these two speeds.

![Figure B2: Basic schematic of the emissions model.](image)

This should be performed at the frequency of the speed trace produced by the traffic model (e.g. 1 Hz, 5 Hz etc.). The resulting emission module will be suitable for both:

- Concurrent processing (so that the traffic model developers will be able to incorporate the module within their program).
- Post-processing (to estimate the emissions over a modelled network using the speed trace files produced by various traffic models)
This work will comprise of the following stages:

- Development of look-up tables that can be used within the emissions model (these might be based on speed and acceleration, speed and speed times acceleration, etc.) for each vehicle category.
- Design the emission module.
- Design a post-processor that can take the speed traces produced by a traffic module and estimate the emissions over the modelled network. This should be adaptable to allow it to work with speed traces produced by different traffic models. The post processor can either be a stand-alone application or designed within a standard application (Excel, Access etc.). The use of specialist applications (e.g. MathCad) should be avoided.
- Run the post-processor over example speed trace files, noting any specific computer requirements (speed, memory, disc size etc.) and the processing time required. Ideally, this should be achieved on a standard office type PC.
- Produce documentation explaining the function of each procedure within the modules and, if applicable, class diagrams.
- Produce user documentation, which should clearly explain how to run the post-processor. This should be aimed at a non-technical user.

**B2 Emission module**

**B2.1 Fleet composition**

As the fleet emissions will be dependant on the composition of the fleet (percentage of heavy-duty vehicles, age/Euro level of the vehicles, fuel etc.), then it will also be necessary to specify the fleet composition. It is envisaged that the simplest way to accomplish this is through the use of one or more data files containing the fleet breakdown. The use of multiple data files would allow different roads within a scheme or different times of day, which may have different fleet compositions, to be evaluated.

**B2.2 Road gradients**

As the gradient of the road effects the emissions and fuel consumption from vehicles, the gradient needs to be included within the model. It is anticipated that several look-up tables will be generated for differing road gradients.

Where the exact gradient is not available, then the emissions can be evaluated through interpolation of the emissions from available gradients.

**B2.3 Fleet-weighted average emissions**

Using look-up tables for each vehicle category will result in emissions for each vehicle category. The emission module will be required to provide the instantaneous weighted emissions for the fleet – based on the appropriate fleet composition database. Two possible methodologies are:
1. The emission module weights the estimated emissions for each vehicle category based on the fleet composition.

Or:

2. At the start of processing, the emissions module derives temporary fleet-weighted look-up tables.

The former is likely be simplest to implement. However, the second option may prove beneficial in terms of processing time, especially when large amounts of data are being processed.

### B2.4 Vehicle categories

The following vehicle categories need to be included:

- Cars
- Vans
- HGVs
- Buses and coaches

The user should be able to specify the fleet composition if local information is available. This should range from a coarse composition – *i.e.* light-duty/heavy-duty split – to more detailed breakdowns. A default fleet compositions should also be provided for various years (2000 to 2025) which should be based on national statistics (*e.g.* NAEI fleet composition), which may be used as a basis for the user defined composition. For example, the user may take the default composition and just modify the light-duty/heavy-duty split, or the user may modify the proportion of pre-Euro 1 to Euro V HGVs. Ideally, this procedure should start at the top ‘coarse’ level and allow the user to ‘drill’ down to the more detailed levels. The user should be able to save any modified compositions with a user-defined name (and, perhaps, some descriptive text) for future use.

#### Cars

The composition of cars needs to include fuel type, vehicle technology (non-cat, catalyst etc.), engine size and Euro level (this can be approximated from the age distribution). Suggested categories to include are listed in Table B1. This gives 6 petrol plus 2 diesel times, combined with up to 6 Euro levels – a total of 46 categories.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Technology</th>
<th>Engine size</th>
<th>Euro level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrol</td>
<td>Non-catalyst (pre Euro I)</td>
<td>Small (&lt; 1.4 l)</td>
<td>Pre Euro I</td>
</tr>
<tr>
<td></td>
<td>Catalyst (Euro I onwards)</td>
<td>Medium (1.4-2.0 l)</td>
<td>Euro I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large (&gt; 2.0)</td>
<td>Euro II</td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>Medium (1.4-2.0 l)</td>
<td>Euro III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large (&gt; 2.0)</td>
<td>Euro IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Euro V)</td>
</tr>
</tbody>
</table>

#### Vans

For vans, the main categories are fuel type and Euro level. Suggested categories are listed in Table B2. This gives 1 petrol plus 1 diesel times up to 6 Euro levels – a total of 12 categories.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Euro level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrol</td>
<td>Pre Euro I</td>
</tr>
<tr>
<td></td>
<td>Euro I</td>
</tr>
<tr>
<td></td>
<td>Euro II</td>
</tr>
<tr>
<td></td>
<td>Euro III</td>
</tr>
<tr>
<td></td>
<td>Euro IV</td>
</tr>
<tr>
<td></td>
<td>(Euro V)</td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
</tr>
</tbody>
</table>

Table B1: Categories for cars.

Table B2: Categories for vans.
**HGVs**

Suggested categories for HGVs are listed in Table. Whereas HGV emission factors are typically classified according to the weight of a HGV, traffic data is more generally classified according to the number of axles. This gives 4 rigid plus 1 artic times 6 Euro levels – a total of 30 categories.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>HGV type</th>
<th>Axles/weight</th>
<th>Euro level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>Rigid</td>
<td>2-axle &lt; 7.5t</td>
<td>Pre Euro I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-axle &gt; 7.5t</td>
<td>Euro I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-axle</td>
<td>Euro II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4-axle</td>
<td>Euro III</td>
</tr>
<tr>
<td></td>
<td>Articulated</td>
<td>5/6 axle</td>
<td>Euro IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Euro V</td>
</tr>
</tbody>
</table>

**Buses and coaches**

Suggested categories for buses and coaches are listed in Table B4. This gives 4 buses plus 1 coach times 6 Euro levels – a total of 30 categories.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Type</th>
<th>Size</th>
<th>Euro level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>Bus</td>
<td>Small</td>
<td>Pre Euro I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>Euro I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Double-decker</td>
<td>Euro II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bendy-bus</td>
<td>Euro III</td>
</tr>
<tr>
<td></td>
<td>Coach</td>
<td></td>
<td>Euro IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Euro V</td>
</tr>
</tbody>
</table>

**B2.5 Vehicle laden categories**

For goods vehicles and buses, the following laden weights need to be considered:
- Un-laden
- Half-laden
- Fully-laden

**B2.6 Gradients**

The following gradients should be considered:
- -6%
- -4%
- -2%
- 0%
- +2%
- +4%
- +6%
B2.7 Driving patterns

A selection of driving patterns should be used that will give good coverage of all possible speed and acceleration combinations:

- that occur in real driving situations.
- that a traffic model may produce.

B2.8 Final module

The emission module should be produced that:
- can be called with the various input parameters.
- will link to the appropriate lookup tables.
- return the emissions as an array.

The source code for this module should be provided. The language used and the structure of the module should be such as to allow easy migration to other languages. This module may be incorporated into traffic models, together with the lookup tables, by the traffic model developers.

A fully working version of the module will need to be developed for use in the post-processor.

B3 Generation of lookup tables

B3.1 PHEM runs

The PHEM model needs to be run for each vehicle category, for each gradient and for each laden factor over all of the drive cycles for that vehicle category. The total possible number of categories are listed in Table B5. It is possible that the PHEM model may be unable to calculate the emissions for some of the combinations – e.g. fully-laden HGVs up a 6% incline, accelerating from rest to maximum speed. This should be ignored, with only valid emissions results used for the subsequent analysis.

Table B5: Number of combinations to evaluate.

<table>
<thead>
<tr>
<th>Category</th>
<th>No of sub-categories</th>
<th>Load</th>
<th>Gradients</th>
<th>Number of categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>48</td>
<td>Unladen</td>
<td>-6% to +6%, step 2% (7)</td>
<td>48<em>1</em>7 = 336</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12<em>1</em>7 = 84</td>
</tr>
<tr>
<td>Vans</td>
<td>12</td>
<td>Half-laden</td>
<td>-6% to +6%, step 2% (7)</td>
<td>30<em>3</em>7 = 630</td>
</tr>
<tr>
<td>HGVs</td>
<td>30</td>
<td>Half-laden</td>
<td>-6% to +6%, step 2% (7)</td>
<td>30<em>3</em>7 = 630</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30<em>1</em>7 = 210</td>
</tr>
<tr>
<td>Buses</td>
<td>30</td>
<td>Half-laden</td>
<td>-6% to +6%, step 2% (7)</td>
<td>30<em>1</em>7 = 210</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total number of categories = 1,260</td>
</tr>
</tbody>
</table>

The PHEM model estimates for CO, HC, NO\textsubscript{x}, PM (diesel vehicles only) and fuel consumption. Although CO\textsubscript{2} is not calculated directly, it can be derived from the standard carbon balance equation, as specified in the Commission Directive 93/116/EC.

The lookup tables need to be derived for the following pollutants: NO\textsubscript{x}, PM and C (where C is the total carbon emitted, based on the carbon content of the CO, HC, CO\textsubscript{2} and PM emissions). This gives a total of 3 * 1,260 = 3,780 lookup tables.
As PM emissions are only available within PHEM for diesel vehicles, PM emissions for petrol fuelled vehicles should be based on average speed curves used within the NAEI/DMRB. However, there should be the capability to extend this at a later date if the appropriate data becomes available.

### B3.2 Data analysis

In addition to providing the overall results, the PHEM model also produces a trace file listing the second by second emissions. The calculations are based on pairs of speeds – using the average speed and accelerations from each adjacent pair of speeds to determine the loads on the engine and hence the emissions. Therefore the speed traces included in the output files are these average speeds between adjacent data points in the original speed trace. Unfortunately, the PHEM trace files do not include the corresponding accelerations. These can be determined from the original speed trace file, though checks may need to be carried out to ensure that the speeds from the input trace and the PHEM output trace correspond to one another.

For each combination of vehicle category, gradient and vehicle load, the data from all the runs need to be compiled together. The corresponding emissions should be gridded against speed and speed * acceleration, using a suitably fine resolution (e.g. 1 km/h steps for the speed and 1 m²/s³ steps for the speed * acceleration). The resulting grid may need to be smoothed and interpolated/extrapolated to cover any missing areas (zeros should not be used, as if these speeds/acceleration are encountered in use, the emissions will be underestimated).

An example of the possible analysis is shown below for the CO emissions resulting from one HGV run (about 600 seconds long). Figure B4 shows the distribution of speed and speed * accelerations from the speed trace (note that for light-duty vehicles, the ranges will be much larger). The resulting CO emissions are shown as a scatter plot in Figure B5. These data has been gridded in Figure B6 and displayed as a surface plot in Figure B7.

As the analysis will produce an extremely large number of lookup tables, a naming strategy needs to be followed to identify each file. Multiple folders could also be used to store the files. The lookup tables could be either in a text or a binary format. If the latter, the format used should be specified. The data should not be encrypted in any way.
Figure B5: PHEM CO emissions derived from the sample speed trace.

Figure B6: Gridded CO emissions.

Figure B7: Surface plot of the CO emissions.
B4  Post-processor

B4.1 Walk-through – post-processing

A provisional walk through of the post processing is as follows:

- The user starts the post-processing tool.
- The fleet composition file is selected.
- If necessary, the user can modify the fleet composition:
  - change the coarse composition – percentage of heavy-duty vehicles.
  - go down into more detail.
  - save the modified fleet composition with a user-defined name for future use.

[it may also be necessary to use different fleet compositions for different section of the scheme. There 
must be some means of associating roads IDs with particular fleet composition files.]

- The speed trace file to process is selected (it should be noted that the layout of the speed trace file may 
vary – with different number of columns, headers, different frequencies and different units (mph or 
km/h). The post-processing module needs to check the data available and the units used. If insufficient 
information is available, then a warning message will be displayed and the processing stopped. It may 
also be useful if the module provides some feedback of the contents of the data file – e.g. descriptive 
headers, data headings, frequency etc.).

- The processor will then work through the speed trace data, passing appropriate data to the emissions 
module and allocating the emissions to the appropriate link. It is anticipated that the file will contain 
data for several thousand vehicles in chronological order. Therefore the processing might consist of a 
single run though the data, temporarily storing the previous position and speed of each vehicle, or may 
consist of multiple runs, initially extracting the speed traces for each individual vehicle before 
evaluating the emissions.

- When processing is complete, the resulting emissions will then be displayed. The user will have the 
option of exporting this information to a text file (suitable for importing into Excel) to various levels 
of details – e.g. emissions over each link or broken down into sections of each link. [Sufficient 
information should be stored to file to allow the user to recall the emission estimates at a later time 
and re-specify the export requirements without having to re-run all the processing].

B4.2 Modelled speed trace files

In order to provide sufficient information to allow the emissions to be determined and allocated to the various 
links, the following data will have to be provided by the traffic models:

- Vehicle category (or separate trace files for separate vehicle categories).
- Time – either time of day or simulation time (time in seconds from start of simulation run).
- Vehicle identifier (number).
- Link identifier (number).
- Position along the link (metres)
- Speed (either km/h or mph)

Other data may also be included in the data files.

B4.3 Allocation of emissions to the links

The speed trace files should identify the link the vehicle is on and give its position along that link. The 
resulting emissions can then be allocated to that link. However, in order to provide greater spatial information 
about the emissions, the link should be sub-divided into smaller sections and the emissions allocated to the 
corresponding section(s).

To illustrate how this might be achieved, Figure B8 shows an examples of the vehicle speed and estimated 
emissions from one vehicle along part of a link. The x-axis shows the position of the vehicle along the link.
The speed trace is also labelled with the position. As the emissions are based on two speeds (in order to
determine the acceleration) the emission data points are positioned in between the speed data points. The
emission data points are shown numbered in ascending order.

![Graph showing speeds and emissions along a link](image)

Figure B8: Example of speeds and emissions of one vehicle along part of a link.

For this example, the link has been sub-divided into one-metre sections. The estimated emissions are allocated
according the position along the link for each pair of input data. For example, the first emission results is
based on speed data for position 501.7 to 503.7 m. The resulting emissions are therefore allocated to link
sections 501, 502 and 503 (in this example, ‘501’ represents the section 501-502 m along the link). The
allocated emissions have been proportioned according to the amount of each section covered – as only 0.3m
(501.7 to 502.0) of section 501 is covered, then the allocation to this section is smaller than to the others. The
allocation of the emissions is illustrated in Figure B9. The bars have been labelled with the emissions data
point number (as per Figure B8) to illustrate how each emissions estimate has been allocated to the sections of
the link.

![Graph showing emissions allocation to sections of a link](image)

Figure B9: Allocation of emissions to sections of the link.

The post-processor will need to keep track of the emissions on each section of each link – adding the
contribution from each vehicle. In the above example, one metre sections have been used. For complex
schemes, this may be too small and make the processing too time consuming. In these cases, coarser sections
may need to be used (e.g. 10 m or 100 m sections).
Abstract

This Report summarises a research project in which the scientific understanding of ‘instantaneous’ emission models for road vehicles was assessed. 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).

The overall aims of this project 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. The project was 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, microsimulation traffic models and air pollution models.
- Task 4: Summary and recommendations for model development and future research.

This Report (Task 4) summarises the work conducted on Tasks 1 to 3. The Report concludes that the instantaneous emission models PHEM and MODEM are equally good at predicting estimation from light-duty vehicles over a trip, even though MODEM is older than PHEM, uses assumptions for Euro III and Euro IV vehicles rather than measurements, and includes no adjustment for the distortion of the emission signal during measurement.

A further conclusions was that one of the main challenges in micro-scale model integration is the matching of the different vehicle types defined in the traffic simulation and emissions components. The systems of vehicle classification required for emission models are generally more complex than those used in traffic models. Ideally, the aim would be to link the most detailed and up-to-date instantaneous emission model to the most appropriate traffic model.

The links between instantaneous emissions and air pollution dispersion modelling tools remain largely untested.

The report provides recommendations and a draft specification for the development of a new instantaneous emission model.