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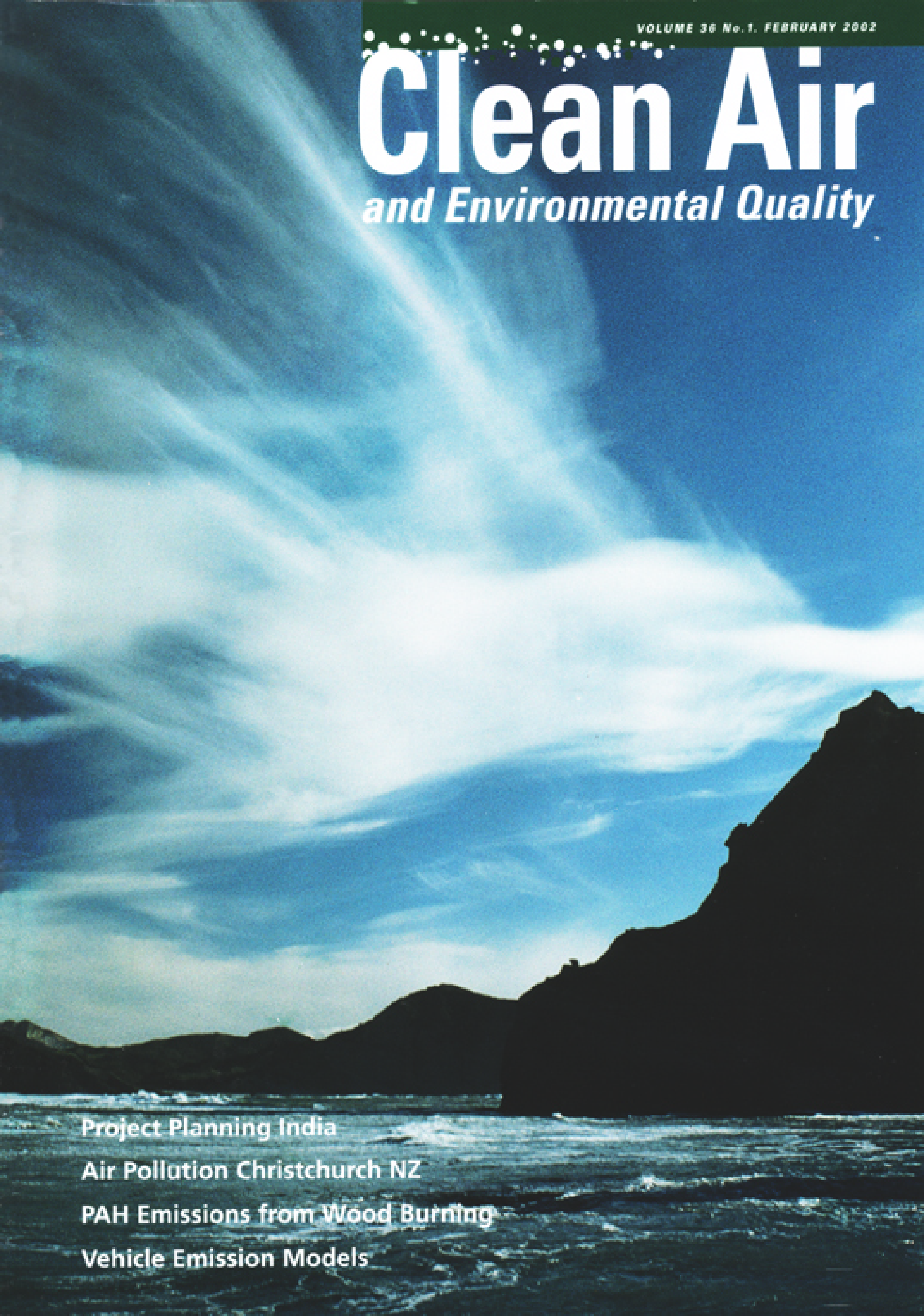

Project Planning India

Air Pollution Christchurch NZ

PAH Emissions from Wood Burning

Vehicle Emission Models

Vehicle Emission Models and their Application – Emission Inventories

R. Smit, R. Ormerod and I. Bridge

ABSTRACT

Different types of Vehicle Emission Models (VEMs) exist around the world and they are used for a wide range of purposes. Each purpose requires different spatial and temporal detail, which impacts on the required model complexity. The way in which VEMs treat vehicle kinematics or driving behaviour is used in this paper to present a VEM classification scheme, that can be used as a framework for the discussion of model types and model applications. Two main model approaches (i.e. model types) are the 'average speed' and the 'modal' approach, but intermediate approaches exist as well. Each model type has its own range of spatial and temporal application. It is concluded that, at this stage, the use of an average speed approach for urban emission inventories allows emission estimates in terms of probability as the best achievable trade-off between model complexity, input data requirements and prediction accuracy. International trends show that we are already heading towards the use of (intermediate) modal VEMs for urban emission inventories.

INTRODUCTION

Emissions of air pollutants from road transport activities make a significant contribution to air quality problems at a range of scales. Issues of concern include localised exposures due to air pollution 'hotspots' in heavy traffic areas, photochemical smog formation in urban-regional airsheds and global warming (enhanced greenhouse effect). With increasing mobility in both developing and developed countries and an ongoing reduction of industrial emissions, the relative impact of road transport is expected to become even more important in the future, despite the penetration of cleaner vehicles into transport fleets. This is indeed the case for Australia where estimated trends show a 20% increase in car passenger kilometres, 88% increase in tonne kilometres and 30% increase in urban congestion levels for the 1996-2015 period (Apelbaum, 1997 as cited in MVEC, 1998). The transportation sector is responsible for approximately 17% of global CO_2 emissions and these emissions are increasing in virtually every part of the world (Walsh, 2000).

The need for high quality emission estimation tools for road traffic is recognised internationally, as they are becoming more crucial for the design and evaluation of air pollution control strategies worldwide and for the evaluation of road projects or transport networks. Although various Vehicle Emission Models (VEMs) exist internationally, there is a continuous need for further improvement and understanding of vehicle emissions in order to develop VEMs that are accurate enough for determination of the most cost-effective emission control policies (Cadle et al. 1999).

This article is the first of two related papers and it begins with a discussion of vehicle emissions and key issues. Subsequently, different VEM types, a number of international models and the direction of current model development are discussed. Finally, their applicability in the investigation of air quality issues is investigated from an international perspective. This paper is not intended to be a research-level review for specialists in vehicle emission models, rather it is intended for general air quality professionals. The second paper will deal more specifically with VEM accuracy and improved urban emission inventories.

VEHICLE EMISSIONS

Road traffic emits many different pollutants but carbon monoxide (CO), hydrocarbons (HC or VOCs), nitrogen oxides (NOx) and particulate matter (PM) are currently regarded as criteria pollutants with respect to urban air quality. Other (secondary) pollutants are generated over time such as photochemical smog, which may give rise to violation of ozone standards. Many specific VOCs found in vehicle emissions are of increasing importance and have been established as toxic, carcinogenic or mutagenic (e.g. benzene, benzo(a)pyrene and 1,3-butadiene). Fuel consumption and greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs), are important with respect to climate change.

TRL (1999) notes that the sum of hot-running exhaust emissions, cold-start exhaust emissions and evaporative emissions form the total emissions from road vehicles. Hot-running emissions are exhaust emissions that occur under 'hot-stabilised' conditions, which means that the engine and the emission control systems (e.g. catalytic converter) have reached their typical operating temperatures. Cold-starts result in enhanced exhaust emissions due to a combination of enriched fuel-air engine operation and reduced catalyst efficiency. An exception can be lower cold-start than hot-stabilised NOx exhaust emissions for non-catalyst technology vehicles.

In recent years, developments in motor vehicle technology (e.g. catalysts) have reduced hot-running exhaust emissions significantly, making the contribution of cold-start emissions a large portion of total emissions (Sabate & Agrawal, 1994). This is aggravated by the fact that a large proportion of journeys are very short so that the full advantages of catalysts are not realised (Sturm et al. 1996). The relative importance of cold-start emissions is particularly high for catalyst-equipped vehicles. For instance, Kemmler et al. (2000) reported that for a EURO3 car, 80% of the total HC emissions were produced in the first 40 seconds after cold-start. However, at present, both the absolute magnitude and relative importance of excess cold-start emissions in emission inventories remain uncertain (Singer et al. 1999).

Evaporative emissions consist of fuel (mainly petrol) hydrocarbon losses through the vehicle's fuel system and include diurnal emissions and hot-soak emissions. It is widely believed that the evaporative losses from spark-ignition vehicles may constitute much or even most of the total automotive HC emissions (Pierson et al. 1999). However, large uncertainties are associated with the ability to accurately characterise evaporative emissions and considerable uncertainty surrounds this part of emission inventories (NRC, 2000).

Actual fuel consumption and exhaust emissions depend on a great many factors including vehicle type, engine type, fuel type, emission control technology, engine condition, condition of emission control equipment, vehicle age, maintenance and tuning, climatic conditions and vehicle operating conditions. Operating conditions of individual vehicles in terms of engine speed, vehicle speed, acceleration, thermal conditions and so forth depend on traffic conditions (congested, urban, motorway, road grade, etc.), vehicle use (short or long trips, frequency of use, etc.) and driving behaviour (gentle or aggressive, gear selection, use of auxiliary equipment, etc.).

Two aspects should be emphasised here due to their emerging relevance to VEMs. The first one is high-emitters. The major cause of high-emitters is the malfunction of specific emission control devices such as three-way catalysts, rather than the gradual deterioration of the emission control system. Remote-sensing results obtained all over the world show a consistent pattern that CO and HC exhaust emission distributions are highly skewed, indicating that a large fraction of the overall fleet emissions (up to 80%) can be attributed to a disproportionately small fraction (about 20%) of the vehicle fleet with excessive emissions (e.g. Sjödin & Lenner, 1995; Zhang et al. 1995; Singh & Huber, 2000). In general, high-emitting vehicles are difficult to characterise statistically as the number of high emitters is relatively small and variation in emission levels is relatively large. This complicates accurate emission modelling.

Secondly, gear changes and high power demand (due to e.g. high accelerations, grade climbing, vehicle accessories such as air-conditioning) are particularly important with respect to modern computer-controlled catalyst-equipped cars as, under these conditions, fuel enrichment is allowed and the catalyst does not perform as effectively (Williams et al. 1994). One sharp acceleration may cause as much pollution as does the entire remaining trip and commanded enrichment is responsible for elevated or 'super' emission episodes, which can be one to several orders of magnitude higher than emissions under stoichiometric engine operation (e.g. Bachman et al. 1996). However, the overall contribution to total emissions can be small due to the low frequency of brief enrichment periods, but may vary greatly by vehicle (Kelly and Groblicki, 1993). Moreover, driving behaviour affects the frequency of enrichment events (Cadle et al. 1996).

VEHICLE EMISSION MODEL TYPES

Different types of VEMs are used to estimate road traffic emissions. In principle, total emissions are calculated by multiplying an **emission factor** (e.g. g/km) with a **mobility parameter**, i.e. the amount of traffic activity that quantifies mobility (e.g. vehicle kilometres travelled). The differentiation of the emission factors and the included model parameters (e.g. in terms of types of pollutants, vehicle categories, road grade, average speed or acceleration) determines the characteristics and the complexity of the model and defines the type of model and its possible area of application (INRETS, 1999).

Here an attempt is made to roughly define and categorise VEMs according to the level of **(dis)aggregation** of both emission factors and mobility parameters. Negrenti (1998a) notes that spatial and temporal scales are key parameters for both the description, and the model selection process. US EPA (2001) has identified three spatial scales in combination with four fundamental analyses (within brackets) that a vehicle emission modelling system will need to perform:

1. **macro-scale** (large or local area emission inventory);
2. **meso-scale** (local area emission inventory or transportation scenario evaluation); and
3. **micro-scale** (transportation scenario evaluation or corridor/intersection emissions analysis).

Although not mentioned by the US EPA, intermediate levels between those three major levels exist as well. Model complexity increases from macro to micro-scale models. There are several general model features that apply to all VEMs. For instance, all VEMs use a certain vehicle classification scheme, which may differ from only a single vehicle to more comprehensive vehicle classes based on differences in engine and emission control technology, emitter-status, vehicle mass and fuel type. Also, VEMs vary in the number and types of pollutants, correction factors (e.g. for road grade, vehicle ageing) and additional options, they include impact assessment of inspection and maintenance programs. The extent to which those model features are included or not (i.e. model complexity) does have an impact on the accuracy of the model output. For instance, the NRC (2000) regards cold-starts as a critical component in the MOBILE emission model. Although these aspects are very important for the actual emission calculations, they are not further elaborated on as we now focus on the different ways which vehicle kinematics are modelled.

Driving conditions or vehicle kinematics have a major impact on emissions, which are largely dependent on engine operation (engine speed and torque). The model parameters used to describe these driving conditions and their variation, are important features of VEMs. These model parameters range from 'not included' to a complex use of parameters such as instantaneous speed and acceleration or throttle position and gear use. In this paper, vehicle kinematics are used for the VEM classification framework as discussed at the start of this section. Two basic emission model approaches have been identified that vary in the way they treat the interaction between vehicle operation and emissions:

1. the **average speed approach**; and
2. the **modal, instantaneous or continuous approach**.

Alternative approaches, such as a fuel-based methodology (e.g. Singer et al. 1999), also exist but are not discussed here.

Macro-scale Modelling

In a macro-scale approach, activity data are directly combined with aggregate emission factors, as is the case for example in *The Energy Workbook for Transport* (AGO, 1998). In a more disaggregated or intermediate macro/meso-scale approach, a limited number of 'road types' are used that are assumed to represent certain driving characteristics, e.g. urban, rural and highway driving conditions. Emission factors are based on driving cycles (trips) reflecting average travel over a large region and aggregate estimates of vehicle activity, e.g. vehicle kilometres travelled (VKT). The total emission calculation is based on a combination of the appropriate emission factors with annual VKT, which are normally taken from statistics on a national level according to different vehicle classes and road types. *The Sydney Metropolitan Air Quality Study* and comparable studies in other states are variants of this approach.

Meso-scale Modelling

The average speed approach, as used in meso-scale VEMs, is the most commonly used methodology to estimate emissions from road traffic and it uses the fact that average emissions over a trip vary according to the average (trip) speed. Thus, average speed is taken to represent driving behavior. The average emission rate for each driving cycle is measured on a chassis dynamometer and assigned to the average speed of that driving cycle in order to derive speed-dependent emission factors for different vehicle classes.

The average speed methodology can be combined with output from traditional four-step travel demand models or traffic counts to estimate emissions on roadway links and/or analysis zones in order to calculate emissions for a specific urban area (US EPA, 2001). These models are generally insensitive to small changes in traffic conditions, e.g. as a result of intersection and signal improvement. Currently employed regional VEMs rely primarily on this average speed approach and internationally well-known meso-scale models are MOBILE (US) and COPERT (EU). These VEMs principally have the same basic structure, but there are considerable differences for instance in the type of data they are based on, the way certain assumptions are made and validated and how many parameters are taken into account (Samaras & Zachariadis, 1994).

MOBILE6 introduces a more disaggregated approach where 'road type and congestion-specific' speed correction factors (e.g. freeways and arterials/collectors with different levels of congestion) are used for the calculation of emission factors and start and running emissions are separated. These speed correction factors are based on separate driving cycles for freeway and non-freeway.

It should be noted that MOBILE6 will still rely heavily on data from the US Federal Test Procedure (FTP) for the basic exhaust emission rates and it is actually the speed correction factors that have been updated. The reason for this change is that the US EPA recognised that freeway and non-freeway have different functional relationships between average speed and vehicle emissions.

Micro-scale Modelling

Real-world vehicle emissions are strongly coupled with driving dynamics and average speed alone does not fully characterise these dynamics. To better capture emission effects associated with a wide range of driving dynamics, researchers have investigated at a more fundamental level modal vehicle operation and have related emissions directly to fundamental operating modes (e.g. idle, acceleration) or operational parameters. Currently, several approaches aim at refining emission models for road traffic by including 'new parameters' in addition to average speed. Those VEMs are often referred to as modal, instantaneous or continuous emission models (NRC, 2000).

Over recent years, international research has focused on the development of more complex instantaneous models to provide a better assessment of finer scale emissions (TRL, 1999; US EPA, 2001). It is generally believed in both the US and the EU that those finer-scale VEMs need to be developed further to support more accurate (localised) emission assessments.

Although complex VEMs such as engine mapping models are used (e.g. Watson et al. 1983), the most basic and most common form of a micro-scale VEM is a multidimensional lookup table or emission factor matrix, where emission rates are a function of parameters such as instantaneous speed and acceleration on a second-by-second basis using certain bands of operating conditions. Matrix data are based on continuous speed and exhaust emission measurements on a chassis dynamometer using different driving cycles. This emission factor matrix can be created for individual vehicles or for a certain vehicle class and fuel type. Emission predictions are based on vehicle kinematics, in the form of e.g. time series of instantaneous speed and acceleration, in combination with these emission matrices. Integration of time intervals then results in emission predictions for a certain road link or trip, or could generate an emission factor for a specific driving mode. An overseas example is the DGV-system (Digitalisierte Grazer Verfahren) where emission levels are calculated based on modal emission data and assigned to different road subsections and crossings within the road network (Sturm et al. 1997). The traffic activity or kinematic data can be generated by microscopic traffic simulation models or instrumented vehicles and are relatively costly (e.g. Hassounah & Miller, 1994, Negrenti, 1998b).

Instead of lookup tables, mathematical algorithms to calculate modal emission rates, derived from statistical (regression) analysis of second-by-second measurement data, have also been used (e.g. Kent & Mudford, 1979).

Another instantaneous methodology is the power-based approach. Power-demand modelling is based on the fact that instantaneous engine power expended at a certain speed is equal to the sum of the power expended to overcome various resistances to the motion. It is assumed that for each vehicle class, the instantaneous emission rate and fuel consumption can be expressed as a (linear) function of the instantaneous engine power exerted by the vehicle (Nguyen et al. 2000). These functions are matched to experimental emission measurement data (Williams et al. 1994).

This power-based approach has been used in Australia for a long time (e.g. Post et al. 1985; Bowyer et al. 1985) and in the US an interest in this approach has led to the recent development of the Comprehensive Modal Emissions Model (CMEM) (e.g. Williams et al. 1999). A current Australian example of a power-based model is the CSIRO Vehicle Emissions Model (CVEM).

More aggregated or meso/micro-scale approaches do exist as well. For instance, the *Swiss/German Handbook of Emission Factors (HBEFA)* specifies emission factors using both vehicle speed and a verbal description of the type of traffic situation that defines the amount of speed variation (TRL, 1999).

As a result, a unique emission factor is applicable for each pollutant, vehicle type and type of traffic situation (e.g. inner-city stop-and-go behaviour). More quantitative meso/micro-scale approaches also exist, e.g. by using aggregate modal emission factors (acceleration, cruise, deceleration, idle) or by introducing a kinematics correction factor for the average speed approach (e.g. Matzoros, 1990; EC, 1995).

MODEL APPLICATION

Vehicle emission models are used for various purposes such as small-scale traffic planning, 'hot-spot' analysis, environmental impact assessments, air quality modelling, emission inventories, national greenhouse gas emission predictions and evaluation of control strategies through emission forecasting.

Each purpose requires different spatial and temporal detail and accuracy and no single VEM is capable of meeting all those applications simultaneously, i.e. each methodology has its own range of application. Importantly, the local availability of emission measurement data and model input data determines the type of model that can be developed and used. Therefore, within the constraints of data availability, end-use consideration of the VEM application should dictate the selection of the appropriate modelling approach (i.e. VEM type), as well as many of the underlying assumptions used in determining the emission factors.

Clear guidance on the application ranges of different VEMs is regarded as being essential and is being acted upon internationally (e.g. TRL, 1999; US EPA, 2001). Some general conclusions can already be drawn:

- Meso-scale and macro-scale VEMs cannot be used for micro-scale applications due to the fact that the necessary spatial and temporal distribution of emissions is lost when the average speed and more aggregated approaches are used; and
- Micro-scale VEMs cannot be used for macro-scale applications due to a prohibitive computational, analytical and data-gathering burden.

Clearly, when a high level of detail is required (i.e. micro-scale application), e.g. for the impact assessment of changing speed limits or for 'hot-spot' analysis, a (possibly intermediate) micro-scale VEM is most appropriate. Similarly, National Pollutant Inventory reporting requirements to estimate total annual emissions within an airshed or the forecasting of national emission levels may only require a macro or intermediate macro/meso-scale VEM. However, this leaves open the question of which VEMs are appropriate for meso-scale applications. For instance, in the case of urban emission inventories, the selection of the appropriate VEM methodology is less clear. One of the key questions is how far the spatial and temporal distribution of emissions needs to be resolved in order to obtain an adequate picture of the situation.

WHAT IS BETTER FOR URBAN EMISSION INVENTORIES – MICRO-SCALE OR MESO-SCALE?

Negrenti (1998b) states that particularly in the case of urban networks characterised by links where the average speed is rather low (typically 10-30km/h), the use of the average speed methodology results in underestimating the effect of speed variability on emissions.

However, Zachariadis and Samaras (1997) argue that the average speed methodology seems to be sufficient for urban emission inventories and urban air quality models (typically a spatial resolution of 1-10km^2), as the use of micro-scale VEMs does not much improve overall emission prediction accuracy, with the only exception probably being a few unusually high or low emission events representing very special traffic situations (e.g. low speed stop-and-go driving). Instead, it is argued that an accurate knowledge of the effects of cold-start emission impacts, road gradient and altitude are of particular importance for urban emission inventories and urban air quality models. In addition, Nguyen et al. (2000) remarks that the average speed methodology is suitable for estimating emissions in air sheds or for multi-link modelling involving a range of driving conditions. Although there is some international discussion on this issue, it seems generally agreed at this stage that average speed can be used for urban emission inventory purposes (e.g. Sturm et al. 1996 and Joumard et al. 2000).

Average speed has been used widely for urban emission inventory purposes (e.g. Sturm et al. 1996, and Joumard et al. 2000). However, current developments are already heading towards more disaggregated approaches to emission estimation for inclusion in urban emission inventories. For example, where MOBILE5 assumes that all types of driving can be characterised by a single parameter, the average vehicle speed, MOBILE6 will use two parameters, i.e. average speed and road type, to improve emissions calculations (NRC, 2000). It is worth noting that those modifications are seen by many as 'interim fixes' until modal VEMs (i.e. accounting for driving conditions) are available. Moreover, models that are able to predict emission inventories and use micro-scale VEMs, are currently being developed in the US, e.g. the TRANSIMS (e.g. Williams et al. 1999) and the MEASURE modelling framework (e.g. Fomunung et al. 2000), and in Australia, e.g. the Australian Air Quality Forecasting System has demonstrated such an approach (Manins et al. 2001).

Recent studies show that emission modelling for older passenger cars (i.e. without a catalyst or with an open-loop catalyst) can be adequately done with the average speed parameter alone, although vehicle type is still important. However, it was found that modern three-way catalyst gasoline cars behave entirely differently from older vehicles, i.e., 50% of total emissions are emitted during very short periods (peaks), which cannot be fully predicted. In addition, large discrepancies between individual vehicles have been found (De Haan & Keller, 2000).

As the percentage of catalyst cars increases over the years to come, it is envisaged by the authors that the effect of driving dynamics will become more and more important in the future. As a result, it might well be that future Australian emission inventories will need to shift to a form of micro-scale approach in order to achieve the best temporal and spatial resolution.

DISCUSSION AND CONCLUSION

Within the constraints of data availability, end-use consideration of the model application should dictate the selection of the appropriate modelling approach, i.e. model type. Micro-scale or intermediate micro/meso-scale VEMs should be used for micro-scale or local scale applications, in order to account for all relevant factors that influence vehicle emissions, e.g. in situations where driving dynamics play an important role. Similarly, less complex macro-scale or intermediate macro/meso-scale VEMs can be used for macro-scale applications, e.g. for trend forecasting of national annual emission levels.

At this stage, meso-scale VEMs can be used for applications such as urban emission inventories, provided that the different driving cycles (on which emission rates are based) adequately represent all types of driving behaviour. Although applying micro-scale or intermediate micro/meso VEMs for emission inventories might be the most accurate approach in the future, limited availability of Australian modal emission data required for accurate micro-scale VEM development is an impediment.

It should also be noted that the quality of traffic activity data (e.g. VKT) are at least as important as the VEM that is used. Traffic activity data are directly used in emission calculations and therefore are an important factor in relation to uncertainty in emission estimates. Clearly, very high resolution emission inventories require high quality, high resolution vehicle activity data to make sure that the advantage of better emission factors is not offset by low quality vehicle activity data.

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GLOSSARY OF TERMS

Driving cycle: Driving cycles provide a single speed-time profile that is representative of urban driving and they are used in legislative vehicle emission test procedures worldwide. In addition, non-legislative cycles have been developed for the estimation of 'real-world' exhaust emissions and fuel consumption.

FTP: The US Federal Test Procedure is used to certify all light-duty vehicles sold in the United States. The FTP driving cycle is based on driving survey data taken in downtown Los Angeles during the 1960s. The Australian ADR27 and ADR37 standards regulate exhaust and evaporative emissions from light duty petrol passenger vehicles and they are equivalent to the FTP72 and FTP75 test cycles.

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