Developments in road traffic emission and fuel consumption modelling: some recent experiences from Europe

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ABSTRACT

Growing concern about health and climate impacts and future tightening of air quality standards will make accurate impact assessment of (new) road infrastructure and policy development increasingly important. As a consequence, there is a need for more accurate (complex) emission models at the local scale. In the development of complex emission models it is important, however, to strike a balance between the level of modelling detail and prediction accuracy and to validate emission modelling results. This paper discusses a number of existing and emerging road traffic emission models in Europe. Particular focus is on a new modeling approach employing statistical techniques and based on a large emissions and fuel consumption tests database.

It appears valuable and feasible to develop an Australian and New Zealand version of this model. This would add to the diversity of current emission modelling in Australia and New Zealand. As a next step, an optimum and agreed-upon modelling framework should be established, based on additional research, model comparison and validation.

Keywords: traffic, models, emissions, Europe, fuel consumption

INTRODUCTION

Transport is a global source of air pollution and greenhouse gas emissions and its importance is growing around the world, as it is for Australia[1]. The problems and issues are (perhaps) surprisingly similar in the affluent nations around the world. From an air quality perspective, road traffic is particularly significant since it emits large quantities of harmful chemicals close to the population. In fact, around the world, road traffic is the dominant anthropogenic source of air pollution in urban areas (e.g. Fenger 1999). We can expect this to remain the case as reductions in individual vehicle emissions (due to e.g. stricter vehicle emissions standards) are at least partially offset by continued growth in traffic and elevated congestion levels.

The relationships between air pollution, greenhouse gas emissions and road traffic are quite complex. As a result, impacts and solutions are commonly evaluated using models (Smit *et al.* 2008a). This occurs at different scales, ranging from local road projects (e.g. hot spot analysis, traffic management) to entire urban or regional transport networks and even national or global emission inventories.

In many European countries national and local authorities are confronted with difficulties in meeting European air quality standards and other environmental policy targets (e.g. National Emission Ceilings). As a consequence, the performance criteria for road traffic emission models have changed over the last decade or so, resulting in a growing need for accurate and versatile models, as will be discussed below.

EMISSION MODELLING IN EUROPE

A number of road traffic emission models are used or being developed in Europe. Probably the most well-known model is COPERT (LAT 2006), which is extensively used for network emission modelling in Europe and other parts of the world. It basically uses the variable "average speed" in (non-)linear algorithms to predict emissions and fuel consumption. Another model is the so-called "Handbuch[2]" (INFRAS 2007), which is a traffic situation model. A traffic situation model uses discrete emission factors (g km^{-1}) for specific traffic situations, which are defined in terms of a textual description. More complex models are used, or are currently being developed, in Europe to predict accurately emissions at a higher resolution. The three most prominent examples are PHEM (Hausberger *et al.* 2003a; Zalinger *et al.* 2005), DIVEM (Atjay *et al.* 2005) and VERSIT+ (Smit *et al.* 2007).

Interestingly, these models show two quite distinctive modelling approaches. PHEM and DIVEM are so-called modal emission models (Smit *et al.* 2002), which compute instantaneous emissions (g s^{-1}) as a function of engine speed, gear shift behaviour, catalyst behaviour and either engine power (PHEM) or brake mean effective pressure and change in manifold pressure (DIVEM). These deterministic models follow a more theoretical approach on the basis that engine power is required to overcome different resistive forces. VERSIT+, on the other hand, is a statistical model and it uses empirical relationships between vehicle emissions and driving behaviour. The next section will explain the reasons for this different approach.

A NEW EMISSION MODELLING APPROACH

Due to increasingly complex engine and emission control technology, emissions of modern vehicles exhibit increasing (inherent) variability. Typically, modern vehicles show low base line emission rates (g s^{-1}), with various short-duration emission peaks. An example of this erratic emissions behaviour is shown in Figure 1 for a three-way catalyst equipped passenger car.

This large variance in emissions has implications for model development. De Haan and Keller (2000), for instance, found it impossible to construct modal emission models that can accurately simulate this irregular emissions behaviour. A simple computation of the correlation between instantaneous power and instantaneous NO_x emissions for the Euro 3 vehicle in Figure 1 confirms this, producing a value of only 0.15, which is quite poor. In response to these concerns, more complex power-based models are being developed in Europe (such as DIVEM), taking into account additional variables such as engine speed (gear shift behaviour), power and catalyst efficiency algorithms. There are, however, still a number of outstanding issues with this approach that are not readily resolved:

1. In reality, there is also a large variability in emission behaviour between different types of vehicles, and even among vehicles of the same brand and model. Individual vehicle emission behaviour in particular traffic conditions (as shown in Figure 1) is really a function of many variables such as engine design, catalyst formulation and size, the calibration of the engine management system, fuel injection strategies, driving behaviour, deterioration of engine and emission control components, to name but a few. So, in order to generate a complex emission model that can truly

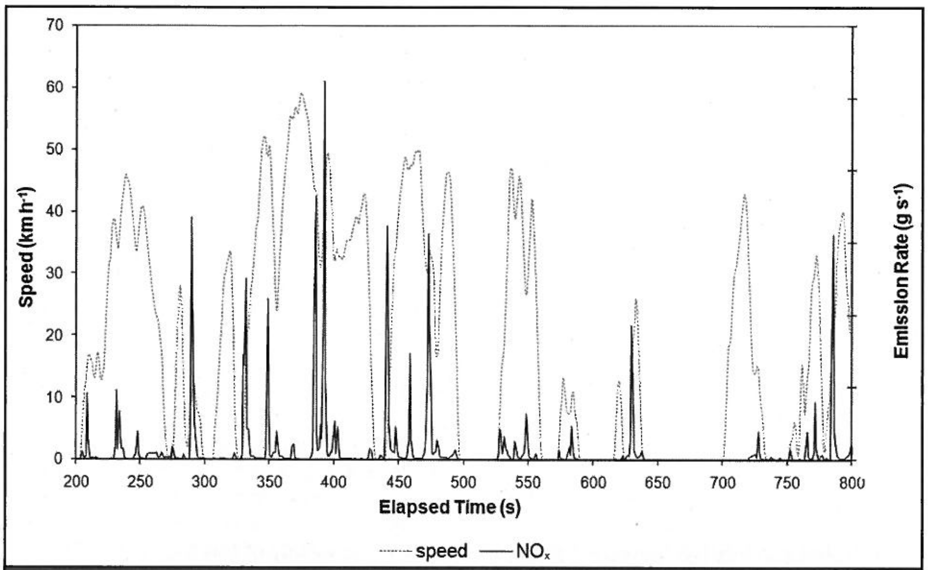

Figure 1 – Example of measured second-by-second speed (urban driving cycle) and NO_x emission rates for a euro 3 petrol vehicle[11]

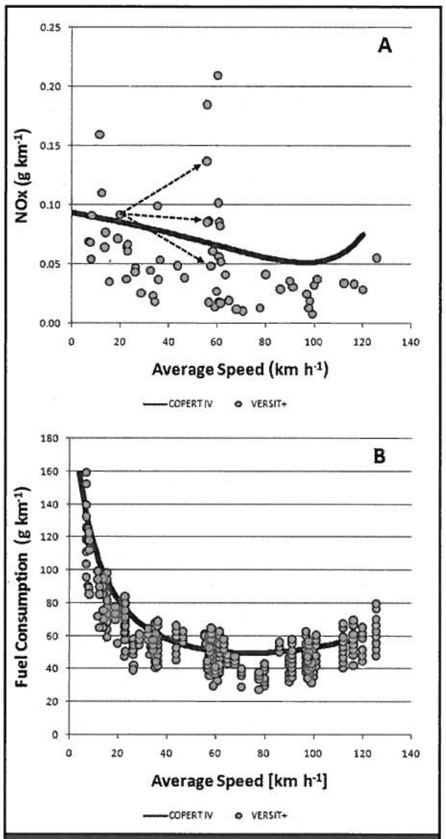

Figure 2 – NO_x emission factors and fuel consumption rates for an average euro 3 petrol vehicle as predicted by COPERT IV and VERSIT+

simulate traffic emissions with lots of different vehicles, a large number of vehicle specific emission models are probably needed. This clearly imposes cost and labour constraints on model development, which may not be feasible.

2. Emissions from diesel vehicles have (traditionally) been modelled quite accurately using existing complex models (e.g. Hausberger *et al.* 2003b), but emission controls in diesel vehicles are becoming more sophisticated (e.g. SCR, NO_x storage catalysts) in response to stricter emission standards. As a consequence, for modern petrol vehicles, accurate modelling of diesel vehicle emissions will become more challenging.
3. Complex models require detailed input data, which may not be available to model users. For instance, to the knowledge of the author, there are no data available on gear shift behaviour in the real-world. This means that assumptions need to be made in order to run the model, introducing unknown errors to model predictions, possibly offsetting accuracy gains.

In response to all these issues, TNO[3] chose to follow a completely different approach and developed a new emission model over the last four years. Instead of developing a detailed complex emission model, an empirical approach was chosen focussing on the overall relationships that emerge from a large vehicle emissions and driving behaviour database. The result is a new model, called VERSIT+ (Smit *et al.* 2007). It is based on approximately 12,000 emission tests that have been conducted at TNO over 153 *real-world* speed-time profiles[4] (driving cycles, an example is presented in Figure 1: dotted line). The model essentially uses multivariate regression functions to model traffic emissions. It uses statistical optimisation software to select the best combination of a pool of fifty driving behaviour variables[5] that are computed on the basis of speed-time profiles. The model also predicts confidence intervals. The input to the VERSIT+ model consists of a speed-time profile and vehicle parameters (*e.g.* mass). Predicted emissions are corrected for ageing, air conditioning use and cold start effects. It was found that VERSIT+ generally predicts observed values well. Observed correlation coefficients for CO, HC, NO_x, PM_{10} and fuel consumption are generally in the 0.80 to 0.95 range, depending on the pollutant and vehicle category, but could be as low as 0.59 in specific cases (a complete overview is presented in Smit *et al.* 2007). Lower correlation coefficients were observed for NO_x emissions from petrol cars, which are due to inherent variability in these emissions, resulting in similarly weak correlations in other models such as DIVEM.

THE NEED FOR ACCURATE EMISSION MODELS

So, is it really necessary to have more accurate emission models? Clearly, the required level of accuracy would depend on the actual application. For instance, an emission model used for "screening" purposes would not be required to be accurate, but needs to be conservative. For other applications, accurate emission predictions are vital, either in an absolute or in a relative sense. In an absolute sense, accurate emission predictions are necessary to compute concentration levels at critical locations, leading to a better assessment of health impacts at these locations. This could, for instance, be a residential area near a busy highway or a child care centre near a busy intersection with a large number of trucks. In a relative sense, there are various (policy) measures that affect driving behaviour and have the potential to improve air quality at the local scale and reduce greenhouse gas emissions.

For instance, specific traffic management measures, aimed at smoothing of traffic flow, would require sensitive and accurate models to predict the magnitude and direction of the effect. Figure 2 illustrates this. It shows predictions made by both an average speed model (COPERT IV, line) and a more complex model (VERSIT+, dots representing specific driving cycles). It can be seen that for traffic situations with different dynamics but similar average speeds VERSIT+ predicts different emission factors[6], whereas COPERT IV predicts the same emissions for all these situations. Suppose now that the implementation of a particular local traffic management measure has smoothed the flow of traffic (i.e. reduced dynamics) and has increased the average speed from 20 to about 55 km h^{-1}. For this particular situation, COPERT IV would always predict a decrease in emissions. In contrast, VERSIT+ could predict either a decrease or an increase in emissions, or even no effect, depending on input with respect to the actual driving behaviour[7] in both the reference and the new traffic situation. This effect is shown in Figure 2 (Chart A) by the dashed arrows.

Although greenhouse gas emissions (Chart B), which correlate strongly to fuel consumption, are less scattered than the NO_x emissions in Chart A, the same issues exist with respect to accuracy. Clearly, for policy makers and transport planners the correct *direction and magnitude* of these effects is vital information for imposing the right (i.e. effective and cost-effective) measures in order to improve on local air quality and reduce greenhouse gas emissions.

The fact that complex models (as VERSIT+) are able to discriminate between various traffic situations with similar average speeds but different dynamics makes these models appropriate and more accurate emission models for applications where the response of emissions to actual traffic conditions is an issue. Since average speed models (as COPERT) do not account for different levels of speed fluctuation at a particular average speed[8], the model only provides accurate predictions for large (urban) road networks, or perhaps substantially large parts of a road network (e.g. 1 km² grid cells)[9].

Another advantage of complex models is that they can be used to develop a modelling framework (bottom-up), including separate models of various levels of complexity, that is consistent. A modelling framework is necessary to match the available traffic input data at different scales with emission models that can run on these inputs. As the demand for resources (costs, labour, computer runtime) to generate and process traffic data increases with road network size, the extent and the level of detail of traffic data is effectively reduced. VERSIT+ has been used to develop spin-off models that can be used for urban emission inventories (Smit *et al.* 2008b) or for national emission predictions (Klein *et al.* 2006). The main aim of VERSIT+ is to balance input data availability at various scales against maximized model accuracy.

ACCURATE EMISSION MODELLING IN AUSTRALIA AND NEW ZEALAND

The reasons for development of complex emission models in Europe would apply probably equally to Australia and New Zealand. So, there would be a need for accurate emission models here. Is it possible then, and is there a need, to develop a VERSIT+ model for Australia and New Zealand? Since VERSIT+ is an empirical model, a lot of emission testing data is required to achieve good overall accuracy. This seems to be the case as there is currently a large body of real-world high-resolution emission testing data available, or being created. These data reflect vehicle operation in Australian road and traffic conditions. Examples are the diesel NEPM vehicle test programs, involving 80 diesel vehicles (Anyon *et al.* 2000), and the currently ongoing NISE 2 study in which over 360 petrol vehicles are tested (Orbital 2005). As emissions data are collected on a second-by-second basis, these programs provide a lot of test data, which will even exceed the TNO database (which is based on total emissions for an entire driving cycle) that was discussed before[10].

There are already a number of deterministic models that have been (and are being) developed. For instance, CSIRO's power based model (e.g. Leung and Williams 2000) predicts instantaneous emission factors (g s^{-1}) for each vehicle class as a function of engine power. Another model (Zito and Taylor 2001) predicts emissions for six fundamental driving modes (e.g. idle, acceleration from idle, cruise). The need for a statistical model such as VERSIT+ depends on the quality of these existing models. At this stage, there is insufficient information to establish how accurate the existing models really are. A model comparison and model validation study (e.g. tunnel study, roadside monitoring, remote-sensing) would be needed to generate more insight. So, it seems that an empirical model, based on a different philosophy than current Australian models, is useful because it would add to possible ways of quantifying road traffic emissions and fuel consumption. But comparison of the different models to independent validation data is highly recommended to identify an agreed-upon methodology in Australia and New Zealand.

In this respect, a point of discussion is how accurate an emission model can be in practice. There is always a trade-off between model accuracy and input accuracy. As was discussed, availability of detailed input data decreases with network size. If a complex emission model were run, requiring more detailed input than were available, simplifying assumptions would need to be made, leading to reduced accuracy. So, there may be an optimum level of modelling detail for a certain application. This hypothetical curve is shown in Figure 3.

It shows that level of (overall) input accuracy (due to availability) decreases with model complexity, whereas (potential) model accuracy increases with model complexity. Prediction accuracy is a function of both input and model accuracy, and a cost-effective optimum level occurs where both curves cross. Beyond this point (more complexity), an increase in prediction accuracy is either small or does not exist. Even a small increase in prediction accuracy is not interesting, as the costs to run the model (data collection, computer runtime) will increase disproportionately.

A research program will be needed to test the validity of this hypothesis. The outcomes of such a program would help to identify the best models at various levels of application.

CONCLUSIONS

Growing concern about health and climate impacts and future tightening of air quality standards will make accurate impact assessment of (new) road infrastructure and policy development increasingly important. As a consequence, there is a growing need for more accurate (complex) emission models at the local scale. In the development of complex emission models it is important, however, to strike a balance between the

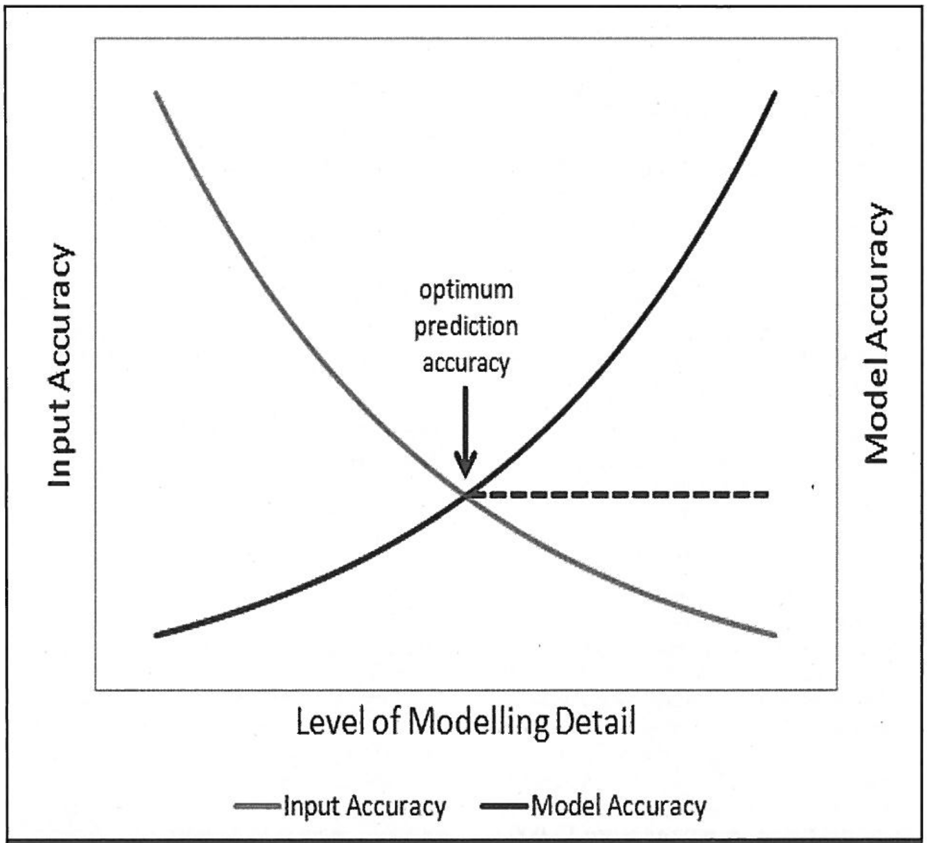

Figure 3 – Hypothetical relationship between input accuracy, model accuracy and level of modelling detail

level of modelling detail and prediction accuracy and to validate emission modelling results. More work is required to increase our understanding in this area.

A new model has recently been developed in Europe that specifically aims to achieve this balance. This model is based on a different philosophy compared to most other models, *i.e.* fully empirical versus more theoretical and deterministic. It appears valuable and feasible to develop an Australian and New Zealand version of this model. This would add to the variety of current emission modelling in Australia and New Zealand. As a next step, an optimum and agreed-upon modelling framework should be established, based on additional research, model comparison and validation.

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ENDNOTES

[1] According to AGO (2007), the majority of transport greenhouse gas emissions in Australia in 2005 came from road traffic (88%) and the remainder from aviation (6%), shipping (3%) and rail (3%). Moreover, total emissions from transport are growing strongly. CO_2-e emissions from transport have increased by 30% in the period 1990–2005 (ABS, 2007) and they are expected to almost double in the period 1990–2020 (BTRE, 2005).

[2] "Handbuch der Emissionsfaktoren des Strassenverkehrs".

[3] TNO is the Netherlands scientific organization for applied science and technology (www.tno.nl).

[4] Road vehicles generally exhibit significantly different emission behaviour in real world situations when compared to standard test conditions. It has been reported that emission factors based on the Euro test-cycles underestimate emissions in "real-world" driving by up to 50–60% (e.g. Joumard et al., 2000). So, real-world test data should be used in the modelling process.

[5] For instance, average speed, coefficient of variation of speed, number of stops, percentage idle time, but also more complex variables combining e.g. instantaneous acceleration, speed and change in acceleration in one equation.

[6] For instance, NO_x emissions from an average Euro 3 petrol car, as predicted by VERSIT+, can vary between about – 80% (driving cycle representing rural driving conditions with eco-friendly gear shift behaviour) to + 200% (driving cycle representing aggressive acceleration behaviour) around the COPERT IV estimate for an average speed of 60 km/h.

[7] It is noted that information on driving behavior (reflected in a driving cycle or a collection of driving patterns) can be obtained from, for instance, an instrumented vehicle driving in a traffic stream or from a microscopic traffic simulation model.

[8] e.g. constant speed versus high levels of speed fluctuation due to congestion.

[9] The (random) error introduced by not fully accounting for speed fluctuation could probably more or less average out. This is because some links will experience higher than average vehicle dynamics and some will experience lower than average driving dynamics. This is based on the assumption that the average speed model reflects average conditions for a particular mean speed, which is something that is not clear and needs to verified.

[10] For example, the NISE 2 modal test data could be broken up in 10 second speed-time profiles with associated emission levels, which would then result in at least about 65 000 data points for each pollutant.

[11] Euro 3 is equivalent to the ADR79/01 emission standard used in Australia. ADR79/01 imposes, for instance, emission standards on all petrol cars manufactured on or after 1 January 2006.