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Vehicle emissions in Australia: from monitoring to modelling

L. Johnson, M. Jamriska, L. Morawska and L. Ferreira
Queensland University of Technology, Australia

Abstract

The South-East Queensland (SEQ) region is one of the fastest growing areas in Australia. This rapid growth and the accompanying increase in vehicle kilometres travelled has brought demand for management methods to deal with air pollution.

This paper reports on a methodology being developed to estimate the likely level of particulate emissions from specific transport proposals. Two main areas are dealt with, namely:

1. on-road measurements of vehicle emissions; and
2. developing, testing and verifying models to estimate particulate emissions.

The paper identifies the need for a particulate emissions model through a review of current modelling practice. It examines the development of monitoring techniques for South-East Queensland and how this data will be utilised for the development of an emissions inventory in SEQ.

Background

Although the negative effects of vehicle emissions have caused concern for some time, particulates from vehicles are only just being recognised as posing one of the most serious health threats. Submicrometer particulates (those smaller than 1 μm) have the potential to cause the greatest health threats since they are more easily inhaled, lodging deep in the lungs where the toxins that they adsorb can be carried into the body (Oberdorster et. al.,[1]; Schwartz et., al., [2]).

Deapite this there has been little recognition of submicrometer particulates in vehicle emissions models. Those models that do include a capability for estimating particulates are concerned with PM_{10} (particle matter smaller than 10 μm) and sometimes $PM_{2.5}$ (particle matter smaller than 2.5 μm), yet the majority of particulates emitted by vehicles are smaller than this (Kittelson [3]).

Information relating vehicle, operating and driver factors to the rate of emissions is widespread for CO, HC and NOx. Relatively few attempts have been made to quantify the behaviour of particulate and submicrometer particle emissions, especially for petrol (spark ignition) vehicles (Cadle et. al., [4]). Despite this, the number concentrations of particles from gasoline vehicles is significant (Ristovski et. al., [5]).

Australian levels of particulate emissions are high and in the major cities recommended health standards are sometimes exceeded. In South-East Queensland, transportation contributes almost 20 percent of particulates emitted and this level is expected to continue to rise well into the next century (AATSE [6]; Dept Env [7]).

The goals of the research project reported here are to:
(I) develop and verify a model for tailpipe particulate emissions taking into account the influence of a range of parameters; and (ii) to apply the model and experimental data to evaluate the total motor vehicle emission strengths in an urban environment, which would become part of an emissions inventory for SE Queensland.

Particulate modelling review

Sixty models were reviewed with only one-third of these found to have a capacity to model particulates. These particulate models are based on very simple equations such as an emissions factor multiplied by Vehicle Kilometres Travelled (VKT). Sometimes there has been allowance made for one or two additional factors, such as the technology (catalyst/non-catalyst/diesel) and aged based mileage accrual (CARB [8]). However, a range of other factors that might affect particulate emissions has not been included in the models to-date.

These models have been used in various studies to calculate emissions factors for use in Australia. These rates are summarised in table one. These rates show the range of values that have been predicted for particulate emissions and shows that many vehicle categories and operating conditions have still not been adequately tested.

It is unsatisfactory to base further emissions calculations on model outputs such as these because:

- they are based on inadequate emissions measurements - figures are often estimates based on outdated studies or extrapolated for different vehicle categories;
- overseas emissions factors are often used that might not be suitable for Australian conditions;
- factors can be based on Australian certification standards rather than "real-

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Table 1: Sample range of particulate emission factors used in Australia

Vehicle Type	Range of rates for PM10 emissions (g/km)
Motor cars (Petrol) 1992/1993	0.01 to 0.133
Heavy Duty Trucks (Petrol) - post 1993	0.05 to 1
Heavy Duty Vehicles (Diesel) 92/93	0.01421 to 17.695
--	--0.03 to 0.05
Heavy Duty Trucks (Petrol) 2011	
Motor cars (Petrol) 2011	0 to 0.03
Heavy Duty Vehicles (Diesel) 2011	1.03

Cosgreve [9];Jakeman [10];Carnovale [11];Parsons [12]; Williams [13].

world" vehicles;

- they are based on very limited vehicle samples;
- the testing routines used might not be realistic reflection of Australian driving conditions;
- results are based on dynamometer tests that might not adequately reflect real world conditions and
- figures are for PM10 rather than submicrometer particulates.

Measurement techniques

For particulate models to be accurate they need to be based on measurement techniques that are an adequate representation of actual on-road conditions. The emission rate for an individual vehicle could be measured under controlled conditions (dynamometer studies) or real-world measurements (equipment loaded car, chasing vehicles etc). While the dynamometer studies offer clear advantages (controlled conditions), they may not necessarily represent real-world emissions as only a limited number of cars under a limited range of conditions are tested.

Real-world assessments of emission rates are most frequently conducted in tunnels (relatively controlled environment) and provide an average parameter, characterising overall vehicle fleet emissions. The real-world measured parameters are used to validate the emissions factors based on dynamometer measurements, which are used as an input parameter for the models predicting pollutants concentration. Both types of studies are necessary to estimate vehicle emissions, which by their nature are complex and dynamic.

When the assessment of emission rates in a tunnel environment is not available, or testing for specific conditions is required, on-road measurements may be applicable. Measuring the concentration of pollutant upwind and downwind from the road, together with traffic and meteorological parameters, allows an estimate of average emission rates. Due to larger uncertainties involved in measured parameters, the final estimate is associated with relatively large errors.

Whatever measurement technique is selected, there are inherent difficulties due to the chemical and physical behaviour of particles and the problems with achieving repeatable results (Katestone Scientific [14]; Cadle et. al., [4]).

To develop an emissions inventory, problems are further compounded due to inaccurate traffic data. Transport demand models tend to be large and regional in nature and that may be restrictive for micro emissions modelling. Miller et. al. [15] found very small errors in assumed average speeds can lead to errors in emissions estimates in the order of 10 percent. A model based on on-road data collection will overcome many of these inadequacies.

Ambient monitoring in SEQ

To develop particulate emissions models for SEQ both dynamometer and ambient measurements are being conducted. This paper presents preliminary results of a study on the particulate emissions from motor vehicles close to a major freeway with the focus on the development and validation of a simple model for 'on-road' assessed emission factors.

A simple Box model based on the mass balance equation has been developed to estimate the average emission rates of a car fleet for the on-road conditions. It assumes that the two main processes affecting the pollutant concentration – emissions and losses are in equilibrium. The emissions originate from the traffic traveling in the box (the main source of particulate), and the losses are due to the airflow (pollutant flux) out of the box. A detailed discussion of the box model approach is given in Jamriska and Morawska [16].

Instrumentation

Two Scanning Mobility Particle Sizers (SMPS) were used for monitoring of particulate pollutants. The SMPS consists of an Electrostatic Classifier (EC) and a Condensation Particle Counter (CPC). The instrument measures number distribution in the particle size range from 0.005 to 0.9 μm using the electrical mobility detection technique. The SMPS uses a bipolar charger in the EC to charge particles to a known charge distribution. The particles are classified according to their ability to traverse an electrical field and are counted by the CPC. Physical settings on the SMPS include adjustments of the flow rates for the monodisperse and polydisperse aerosol, and for the excess and sheath air. These flow rates determine the measurable size range for a given sampling time. A complete sample may be taken in as little as 2 minutes. Both instruments were calibrated prior to the measurements, and the results were corrected for particle losses in the sampling lines.

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The meteorological parameters at the tested site were measured by an automatic environmental station, allowing continuous monitoring and recording of horizontal wind direction and velocity. Parameters were averaged over the six-minute intervals.

Sampling sites

Two sampling sites, a monitoring and a reference site, have been selected for the simultaneous monitoring of traffic related pollutants. *The* monitoring site selected represents typical freeway traffic conditions with vehicle travelling in a flowing traffic mode at a steady speed of approximately 100 km/h. The road grade is negligible, and, due to the distance from the city (approximately 10 km), it is assumed that vehicle engines are operating in a steady temperature mode. The vehicle fleet consists of approximately 94% passenger cars, less than 5% light and heavy trucks and less than 1% buses. The freeway consists of 4 lanes, with 2 lanes in each direction. The topography of the site can be characterised as a semi-open, street canyon type.

The instrumentation was located on a bridge across the freeway with negligible local traffic. The experimental set-up allowed continuous monitoring of pollutant concentration, traffic and local meteorological parameters, in five minutes intervals. The traffic data were monitored by a permanent traffic system, providing the vehicle count. The traffic was assessed from the survey data and from a manual (video-recording) count.

The reference site was located at the top of a 6-storey high building approximately 200 m from the freeway. While the effect of the traffic emission from the freeway was detectable, it was not significant, and as such the data can be used as reference (background) readings.

Results

The Box model has been applied and tested under the on-road conditions with the road running through a semi-open street canyon. A set of preliminary measurements was conducted to assess the Box model input parameters.

Horizontal profiles of particle concentration measured at the monitoring site showed relatively uniform distribution of particulate, thus validating the perfect mixing assumption. The measurements were conducted at three sampling points – at both ends and in the middle of the bridge at the heights of 3 m and 7 m. Based on these results the sampling point above the centre line of the freeway was selected as a representative location for sampling.

Figure 1 shows typical particle size distributions (spectra) measured at the monitoring site. The spectrum is bimodal, indicating the presence of two main sources. The first peak, approximately around 0.020-0.030 μm is related to the emissions by spark ignition (petrol) vehicles; the second peak around 0.060-0.070 micron is attributed to diesel vehicle emissions. The fleet mix causes the

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dominance of the first peak, with more than 95% of vehicles being petrol operated, even though the diesel vehicles are significantly stronger emitters.

Particle concentrations measured at the monitoring and reference sites

Figure 2 shows the time series of total particle concentration, measured simultaneously at the monitoring and reference site. The reference site concentrations fluctuated around $7.0x10^3$-$1.0x10^4$ particle.cm^{-3}. The concentration measured at the monitoring sites show more rapid variations between $2.0x10^4$ to $6x10^4$ particle.cm^{-3}. This could be attributed mainly to the changes in the wind velocity and direction, as the traffic flow for this monitoring period was steady. The normal wind component (projection of the wind velocity into the direction perpendicular to the road) and the variation in net concentration of particles attributed to the traffic emissions, is presented in figure 3. It can be seen that the dispersion effect governs the fluctuation in particle concentration. The traffic emissions increased the concentration levels by up to $5.0x10^4$ particle.cm^{-3}. Considering that the measurements were conducted outside the peak traffic period, it is a conservative estimate of the concentration levels likely to occur in the vicinity of busy roads.

Assessment of the average emission factors for particulate number/mass

Figure 4 shows average emission rates calculated by the Box model, relevant to the input parameters presented above. The average for particle number emission rates presented was $1.07x10^{11}$ ($3.4x10^{11}$) particles/vehicle km (calculated for average height equal to 6.6 m and 8.4 m, respectively).

The average number and mass emission rates obtained from dynamometer studies (Morawska et al., [17]) for petrol vehicles were $(4.9\text{-}2.4)x10^{11}$ particle/vehicle km and $(3.9\text{-}13.4)x10^{-2}$ mg/vehicle km, respectively . For diesel vehicles the corresponding emission rates were $(5.4\text{-}7.7)x10^{13}$ particle/vehicle km and $(5.3\text{-}8.1)x10^1$ mg/ vehicle km. Similar results have been reported by Graskow et al.'[18]. These values are in reasonable good agreement with the emission rates assessed by the Box model.

Towards a new particulate model for SEQ

Given that the box model has proven to be valid and can be applied to the assessment of emissions factors, traffic data has been collected and analysed from the site. Video outputs of traffic on the roadway will be correlated with particulate measurements to see how periods of varying speed, congestion and traffic correspond to particulate counts. Video identification of vehicles has been carried out to see how the age of vehicles driven, types of vehicles on the road, level of congestion and speed vary with time. Gaseous emissions have also been measured for the site and will be compared with particulate trends to determine

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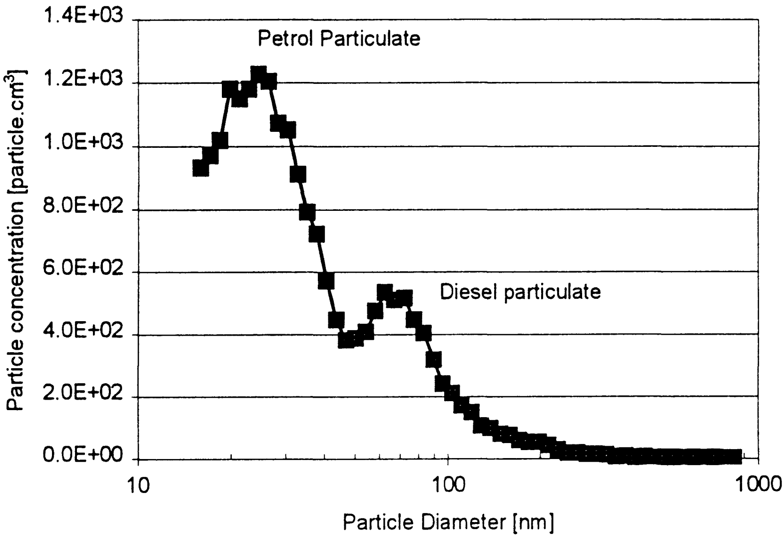

Figure 1: A typical particle size distribution measured at the monitoring site

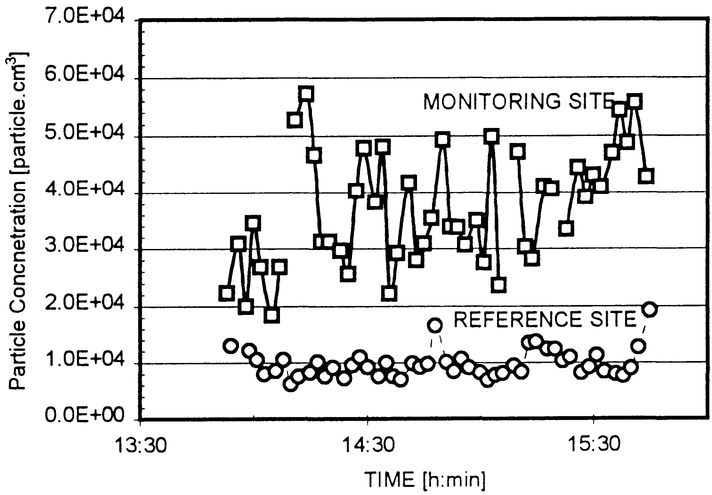

Figure 2: Total particle concentration measured at the monitoring and reference sites

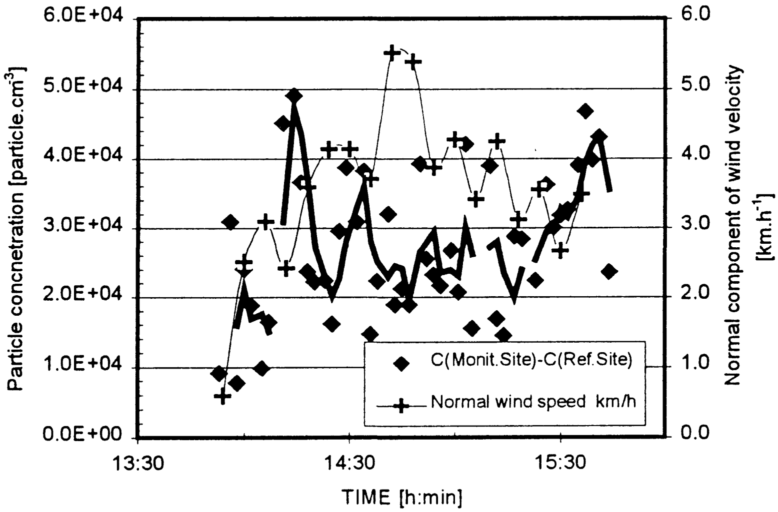

Figure 3: Concentration of particulate at the monitoring site (background removed) and normal wind speed component

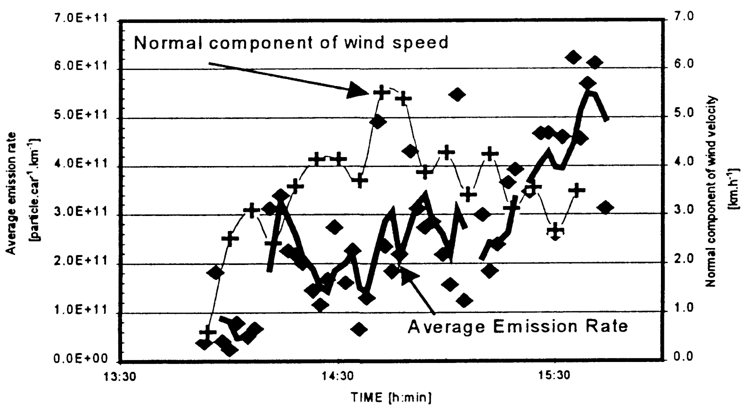

Figure 4: Average emission rate (particle number) and normal wind speed component

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any relationship between pollutants. Data on ambient temperatures and wind direction and speed has also been collected from the Bureau of Meteorology. Relationships between the various data sets will be examined and hypotheses made to explain likely reasons for fluctuations in emissions. An average g/km emissions rate for vehicles on the road will be calculated.

Outputs from recently completed dynamometer studies of particulate emissions from the USA and QUT, together with the data compiled from the ambient study will be used to determine average emissions rates for vehicles according to factors such as vehicle age, technology type, load, speed and mode of operation. These will be cross-checked by performing a total calculation for the freeway measured in this project, based on the traffic composition determined from analysis. Average correction factors specific to SEQ conditions will be developed for use in the model. The model will be verified against the ambient measurements and dynamometer tests and could be further developed for calculating a vehicle emissions inventory.

Conclusions

A simple mathematical model for the assessment of traffic related emission rates at the on-road conditions has been developed. The model was validated with experimental data obtained from a set of pilot studies conducted at a freeway. The obtained number and mass emission rates were in relatively good agreement with the results of dynamometric studies. The results shown here are part of a larger study, focussing on the long term monitoring of traffic-related particulate and gaseous emissions.

In conjunction with this monitoring program a tailpipe particulate emissions model is being developed. The model will account for the relationship between particulate emissions and various vehicle and operating parameters. It will be able to predict the behaviour of fine particulates. The aim is to help address the shortcomings identified in pre-existing particulate models.

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