Transactions on the Built Environment vol 52, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Estimation of motor vehicle emission factors from road measurements of pollutant concentrations

L. Morawska[1], L. Ferreira[2], M. Jamriska[1], S. Thomas[1] & F. McGregor[2]
[1]*Centre for Medical and Health Physics, Queensland University of Technology, Australia*
[2]*Physical Infrastructure Centre, Queensland University of Technology, Australia*

Abstract

Motor vehicle emission factors for application in traffic/transport models are often estimated indirectly, through measurements of pollutant concentrations in the close vicinity of a road link. Such an approach provides insight into total vehicle fleet emissions on that link. However, estimation of emission factors from the measured concentration raises a set of complex issues. The concentrations depend not only on the emission factors, but also to a large degree on meteorological factors, as well as on the topography of the area.

Using the number/mass balance model, a theoretical relationship was developed earlier that allows for calculation of emission factors from the concentrations measured at a specific point above the road, taking into account wind as the only removal mechanism of the emitted pollutants. Using this model, average emission factors for all vehicles on the road can be estimated and then used to arrive at emission factors for individual types of vehicles, given a known vehicle fleet composition.

The work presented here is an extension of the model to include the effect of humidity and temperature, as well as topographical aspects, on the concentrations measured. Starting from the principles of combustion processes, as well as of the dynamics of pollutant interaction and transport, some of the

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general mechanisms affecting emissions or concentrations were included in the model. The empirical dependencies were derived from the results of extensive monitoring of traffic flow and associated emissions at two city sites. The latter included a freeway link and a major signal controlled urban arterial link. The model and experimental results can be applied to estimate average emission factors from measurements conducted at any road link.

Introduction

An emission factor is typically defined as the amount of a chemical species emitted per unit mass of fuel burned or per a defined task performed. The former is often referred to as *mass-based emission factor* and has a unit such as g/kg. The latter can be called *task-based emission factor*. The unit of task-based emission factor depends on the definition of tasks. For example, a task can be a certain distance driven by a motor vehicle and thus the unit may be g/km (Winebrake [1]; Gertler [2]). Knowledge of motor vehicle emission factors that are used as inputs into traffic and transport models is necessary for estimation of current as well as prediction of future traffic and transport contribution to air pollution.

There are a number of methods for estimation of motor vehicle emission factors and the most common experimental methods include: (i) direct measurements of pollutant emissions from vehicles placed on a dynamometer and run through a certain driving cycle, and (ii) indirect estimation through measurements of pollutant concentrations in the close vicinity to a road link. Both these methods have advantages and limitations. In particular, the first method provides the emission factors of a relatively small number of vehicles, but for very well controlled conditions, that, however, may not be representative for vehicles on a road. The second method provides emission factors of the whole motor vehicle fleet on this road link, where conditions are not controlled either in terms of meteorological or traffic conditions.

One of the complexities associated with application of the second method is that while for traffic/transport models emission factors for individual types of vehicles are required, it is not the emission factors that are measured, but the concentrations of pollutants in the air. Concentrations of pollutants in the air depend on the emission factors, but also to a high degree on meteorological factors and often on the topography of the area. Emission factors depend to a much weaker extent on some of the meteorological factors and the dependencies are likely to be different than between concentrations in the air and meteorological factors. Table 1 summarises some known or hypothesised trends in dependencies between emission factors, concentrations in the air and meteorological parameters.

In addition to the above dependencies, vehicle emission factors depend on a number of factors related specifically to vehicle characteristics or fuel used and on traffic flow variables such as average speeds and driving cycles. Thus, in conducting analyses and interpretation of the data collected from roadside measurements, a clear understanding should be developed on what are the calculated parameters, what is the role of individual factors and what is the meaning of the correlations.

Table 1 Dependencies between emission factors, concentrations in the air and meteorological parameters

	Ambient Temperature	Humidity	Wind speed	Rain	Topography
Emission factors	Strong dependence on initial temperature of the engine (that can depend on ambient temperature, particularly extreme) Weaker or no dependence for a hot engine	Possible dependence	No dependence	No dependence	No dependence
Airborne concentration in the immediate proximity of the road	No dependence	No dependence or weak dependence	Strong dependence	Strong dependence	Dependence

The work presented here is part of a larger project aimed at estimation of emission factors of the motor vehicle fleet in Brisbane, Australia through extensive measurements conducted at two urban sites. During the course of the project a large body of data was collected including particle number and size distribution, concentration of inorganic gases, elemental composition of particles, meteorological parameters, total traffic count and videotapes of the traffic to provide counts of individual types of vehicles. The specific focus of this project from the emission side has been on fine and ultra fine particles. The methodology developed for the program, the instrumentation used as well as data analyses from the pilot stage of the program have been presented elsewhere (Johnson [3]). This paper presents an approach that has been developed to estimate the emission factors form the concentrations measured considering meteorological and topographical aspects. The main consideration of this work was to develop an understanding of the effect of meteorological conditions on the airborne concentrations after the emissions. Changes to the concentration after the emission, if not accounted for, can result in systematic errors in the emission factors calculated using the concentrations.

The role of meteorological factors on emission factors and on measured concentrations

The role of temperature. It is known from the literature that low ambient temperature affects vehicle emission factors resulting in different emissions at lower temperatures than at higher. The effect of ambient temperature in the range from 17 to 48^{0}C and other parameters on the particle number and concentration measured from a diluted exhaust have been investigated under laboratory conditions for a medium–duty, turbocharged, aftercooled, direct–injection Diesel engine (Khalek [4]). The authors concluded that the dilution temperature influences the nucleation process and the growth, and thus resulted in the increased diesel particle number concentration at lower dilution temperatures.

There is also an effect of cold versus hot vehicle start, which is more an effect of engine temperature than ambient temperature, but could also be affected by the ambient temperature. For example, a cold vehicle starting at a temperature of – 20 C will take longer to achieve engine temperature of several hundred degrees, than a cold vehicle starting at +20 C.

The other question is whether the temperature is expected to affect airborne particle concentrations. There is no obvious physical justification for any direct effect, based on the understanding of particle dynamics for the range of the temperatures measured. If any, temperature could have an effect on other atmospherics parameters (for example humidity), and thus indirectly, through that parameter, affect the concentrations. But since the effect is indirect, the primary effect of the parameters affected by temperature should be taken into consideration not the temperature.

The effect of humidity. Humidity can have an effect on the combustion process and thus on the emission factors. The influence of relative humidity on particle number concentration was investigated by (Khalek [4]) under laboratory conditions for a diesel engine at 15% and 40% relative humidity of the air in a dilution tunnel. The number concentration of particles below 30 nm increased by up to 70% at higher relative humidity. The authors concluded that although the measurements were conducted in a dilution tunnel under controlled conditions, the general findings of this study can also be extended to real-world situations, where the temperature and relative humidity of ambient air represent the test conditions.

Humidity also has a potential effect on particle concentrations by affecting ambient particle dynamics. It can affect particle size depending on particle hygroscopic properties and resulting either in shrinking (by evaporation, if high water content particles are introduced to dry air) or growth, if lower water content particles are introduced to moist air. Through the effect on particle size, humidity can have a certain effect on particle concentration, as the rate of particle coagulation is dependent on the size. The point, however is, that the rate of coagulation is strongly dependent on particle concentration (square of concentration) for any particle size, and thus the concentration is the main determinant of the rate of coagulation rather than particle size. In addition, at the concentrations encountered at the road sites of the order of 10^4 up to 10^5 particles/cm^3, the rate of coagulation is slower compared to the speed of particle removal by wind action.

Determination of emission factors from concentrations using the "box model"

A simple box model based on the mass balance equation was developed for the purpose of this study to estimate the average emission factors of a car fleet for on-road conditions (Jamriska [5]). This model is a modification of models reported in the literature that have been based on a similar principle (Bullin [6]; Bullin [7]; Hlavinka [8]; Ishikawa [9]).

The model assumes that the two main processes affecting the pollutant concentration – emissions and losses are in equilibrium. A small section of a road – a box – is isolated for the purpose of modelling. The emissions originate from traffic travelling in the box (which constitute the main source of pollution), and losses are due to airflow carrying the pollutant out of the box. The latter is dominated by wind speed and direction. The effects of sinks, such as gravitational deposition of particles or of other processes affecting pollutant characteristics are assumed negligible. This assumption is not a limitation of the model neither for fine and ultra fine particles nor for gaseous emissions. The time scale of the processes affecting particle or gaseous characteristics such as, for example, coagulation or photochemical processes is larger than the residence time of the pollutants in the box, and for fine particles, gravitational deposition plays a negligible role. The model also assumes that: the pollutant concentration within the box is uniform, meaning perfect mixing; the dimensions of the box (height and width) could be experimentally determined; and the angle between wind and the road is at least 20^0, with wind velocity at least 3 km h^{-1} or more (Bullin [6]). The last assumption is necessary for assuring that the pollutants are not contained within the investigated box or in the "boxes" proceeding the one being investigated (previous segments of the road).

The outcome expected from using this model, is emission factor of all vehicles or of individual types of vehicles for particular motion modes. The prediction of emission factors using the box model requires a set of input parameters related to the box geometry as well as to meteorological and traffic conditions. The methodology for determination of the input parameters is presented in detail elsewhere (Jamriska [5]).

As the focus of this work was on particulate matter, the equations for the box model are presented for particles as the pollutant of interest and for particle number or mass as the targeted characteristics. The same approach can be used

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for gaseous pollutants as well, since there is no restriction in the method presented that would limit it to particles only. Using the number/mass balance approach, the relationship linking emission factors with the measured concentrations can be expressed as (Jamriska [5]):

$$E_{Aver} = \frac{(C_B(t) - C_0(t))(v_x H + v_z W)}{N(t)} \qquad [1]$$

where:

$C_B(t)$ - particle concentration in the box [particle m^{-3}, or mg m^{-3}]
$C_0(t)$ - particle concentration outside of the box (background) [particle m^{-3}, or mg m^{-3}]
H – height of box [m] (determined semi-empirically)
W – width of box [m] (width of the road canyon)
v_z - normal component of vertical wind velocity [m s^{-1}]
v_x - normal component of horizontal wind velocity [m s^{-1}]

$N(t)$ - traffic volume [car s^{-1}]
E_{Aver} - average emission factor [particles $km^{-1}car^{-1}$; or mg $km^{-1}.car^{-1}$]

Thus from experimental data on pollutant concentration, E_{Aver}, the emission factor averaging emission factors of all vehicles, is calculated in the first instance. If vehicle composition is available, the relationship between the overall average emission factor and the emission factors of individual vehicle types can be calculated as:

$$\sum_i^n E^i_{motion\ mode} N^i(t) = (C_B(t) - C_0(t))(v_x H + v_z W) \qquad [2]$$

where i represents vehicle type out of n types identified (for example: i = 1 for diesel bus, i = 2 for petrol passenger car, etc)

The unknown parameters in equation 2 are emission factors for individual types of vehicles, and thus the number of unknowns is equal to the number of vehicle types into which the vehicle fleet was divided.

Extension of the Box model to include the meteorological and topographical factors

The "box model" allows for calculation of emission factors from the concentrations measured taking into account wind as the only removal mechanisms of pollutants from the box. As discussed above, wind is not the only parameter affecting pollutant concentrations in the air and the dependence of other meteorological factors and topography on the measured concentration should be taken into account. Some of these dependencies are general (like any dependence on humidity or temperature), others site specific (topography). For example, for all the sites, an increase of wind should result in a decrease of pollutant concentrations in the air, but the function describing the dependence (curve) can be different.

The meteorological conditions considered are temperature and relative humidity and their role could be either in affecting the combustion process and thus the emission factors or affecting the measured concentration (affecting pollutant characteristics after the emissions). If the effect is on emission factors, then from the experimental data a functional dependence on the factors could be obtained, which will be used in traffic models. If the effect is on the measured concentration, then correction factors for these conditions should be determined and used to recalculate the measured concentration, before individual emission factors are calculated. In summary, the meteorological and topographical factors can be introduced to equation [2] for calculation of emission factors in the following way:

$$\sum_{i}^{n} E^{i}_{motion\ mode}(T, humidity)N^{i}(t) = (C_B(t).p(RH) - C_o(t).p(RH))(v_x H + v_2 W)L \quad [3]$$

where p(RH) is the function relating concentration to the RH, and L is topographical factor.

Analyses of the effect of temperature and humidity on particle emission factors and the concentrations

Temperature. In the case of the measurements conducted in this study it can be assumed with confidence that by the time most of the vehicles have travelled to the monitoring sites (because of the location of the sites), an equilibrium engine temperature has been achieved and the emissions did not depend on the starting conditions. The main question could be to what extent the combustion process is affected by ambient temperatures in the range of about +15 to +30 C encountered in these measurements.

In order to identify the effect of air temperature on particle concentration, two statistical methods were used. In the first instance the null hypothesis of no correlation between these two parameters was tested using the Pearson product moment correlation technique. In order to exclude the effect of the "primary" variables, such as traffic flow rate and wind velocity on measured concentration levels, a data segmentation technique was applied. Only data segments with the values of primary variables within a defined narrow range were selected for statistical analyses. The correlation analyses applied on the data segments from both measuring sites indicated no statistically significant (p=0.1 and 0.05) correlation between measured particle concentration levels and air temperature.

Secondly, using a Multivariate Data Analysis technique, the relationship between all measured variables was investigated. Principal Component Analysis (PCA) was applied on the complete set of data in order to separate the main sources in data variation. The variables included in PCA were particle concentration, size distribution, traffic flow rate, wind velocity and direction, air temperature, humidity and rainfall. The PCs with factor loadings with magnitudes greater than 0.3 were considered as providing the main source of variation for each PC. Under these guidelines temperature did not account for any sources of variation. Instead, the sources of variation that may have been interpreted as correlated to temperature were always correlated to another variable, such as traffic flowrate, that coincidentally changed with changing temperature.

Humidity. The range of relative humidity encountered during these measurements was very broad from about 20% to almost 100%. Similarly to air temperature, the effect of relative humidity on particle characteristics has been investigated using the correlation analyses and data segmentation techniques as well as PCA analyses. Correlation analyses on segmented data showed that there is a statistically significant correlation between particle concentration and relative humidity. With an increased relative humidity the concentration increases almost linearly with the increase being more dominant in the nuclei mode (in the size range 20-30 nm) as compared to the accumulation mode (size range 60-80 nm). This may indicate a higher rate of formation of nanoparticles due to an increased amount of water vapour required for nucleation processes affecting particle formation.

PCA analyses conducted on the data set resulted, however, in a somewhat different conclusion. For the site where vehicles travel predominantly at a high speed of about 100 km/h and most of them are petrol fuelled passenger cars (Tora St), the PCA of the complete data set indicated that the combined correlated information from particle number concentration and RH did not generate any sources of variation in any of the PCs. The PCA of the complete data set for the second site that was near traffic lights and where a higher fraction of vehicles were diesel trucks (Ipswich Rd) also did not reveal linear combinations involving relative humidity and particle number concentration as major sources of variation in the data in the first five PCs. However, for PC7 and PC8, relationships existed between RH and number concentration accounting for a source of variation in the data. These PCs when combined, only account for < 7% of the total variance. Similar analyses conducted for the Ipswich Rd data showed that a positive relationship between humidity and particle number concentrations exists for weekdays. Furthermore, increases in the particle numbers with humidity are more likely to be observed under calmer wind conditions as evident in the negative relationships between the two variables and the wind speed vector.

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To investigate the effects of relative humidity upon particle number concentrations in an ambient urban environment, correlation analyses corresponding to Pearson-product moment correlations were performed upon the atmospheric data that has been collected since 1995 at the Environmental Protection Agency and the Queensland University of Technology Air Monitoring and Research Station located in the Brisbane CBD. There was no correlation observed between relative humidity and particle number concentration (R = 0.03) for the entire data set. Only for selected episodes of wind condition bringing air from the nearby freeway an improved but still insignificant correlation was observed between the two variables (R = 0.16).

Conclusions

From the analyses of a potential effect of temperature in the range from 15 to 30^0C and relative humidity in the range from 20 to 100% on vehicle emission factors and on particle ambient concentration, it can be concluded that:

1. The temperature does not appear to have any effect and thus no correction to the Box model for the temperature is required; and
2. Relative humidity does not appear to have an effect on particle concentration in the air, but may have an effect on emission factors. The effect may be different for different types of vehicles, with higher impact possible on diesel vehicles.

Thus, the formulae for calculation of emission factors from particle concentration measured will take the form:

$$\sum_{i}^{n} E^{i}_{motion\ mode}\left(humidity \right) N^{i}(t) = \left(C_B(t) - C_o(t)\right)\left(v_x H + v_2 W\right)L \qquad [4]$$

The topographical factors are different for different sites. They do not affect motor emission processes and thus do not result in changes in motor vehicle emission factors. Since the topographical factors affect the concentrations measured, (the concentrations measured would be different if the topographical effects were not present, despite emission factors remaining the same) there is a need to determine correction coefficients for the topographical effects before proceeding to calculate individual emission factors.

The work reported here will be followed by an analysis of the relationships between emissions factors and traffic flow characteristics, using data collected for several urban road links. The relative contributions of variables such as traffic speeds, levels of congestion, and vehicle fleet composition will be investigated. The results will yield previously unavailable data on particle emissions, disaggregated by vehicle size and age, fuel type, and travel speed. It will be possible to estimate the likely impact on particle and gaseous emissions from area-wide transport/land use policies and plans. When used in conjunction with travel demand models, the results can be useful to test strategies such as:

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(a) Significantly increasing the overall share of trips made by public transport;
(b) Reducing average trip length through increased residential densities; increases in 'in-fill' in inner urban areas; planning restrictions on urban 'sprawl'; and employment location policies; increases in telecommuting;
(c) Introducing travel demand management measures that will have an area-wide impact (eg: parking supply and pricing; higher vehicle occupancies; variable road pricing; fuel levies; and public transport pricing and level of service provision.); and
(d) Changing vehicle fleet characteristics and fuel technologies.

Acknowledgments

This work was supported by the Queensland Department of Transport and ARC SPIRT grant 9800151.

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