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Derivation of motor vehicle tailpipe particle emission factors suitable for modelling urban fleet emissions and air quality assessments

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Abstract

Background, aim, and scope Urban motor vehicle fleets are a major source of particulate matter pollution, especially of ultrafine particles (diameters < 0.1 µm), and exposure to particulate matter has known serious health effects. A considerable body of literature is available on vehicle particle emission factors derived using a wide range of different measurement methods for different particle sizes, conducted in different parts of the world. Therefore the choice as to which are the most suitable particle emission factors to use in transport modelling and health impact assessments presented as a very difficult task. The aim of this study was to derive a comprehensive set of tailpipe particle emission factors for different vehicle and road type combinations, covering the full size range of particles emitted, which are suitable for modelling urban fleet emissions.

Materials and methods A large body of data available in the international literature on particle emission factors for motor vehicles derived from measurement studies was compiled and subjected to advanced statistical analysis, to determine the most suitable emission factors to use in modelling urban fleet emissions.

Results This analysis resulted in the development of five statistical models which explained 86%, 93%, 87%, 65% and 47% of the variation in published emission factors for particle number, particle volume, PM_1, $PM_{2.5}$ and PM_{10} respectively. A sixth model for total particle mass was proposed but no significant explanatory variables were identified in the analysis. From the outputs of these statistical models, the most suitable particle emission factors were selected. This selection was based on examination of the statistical robustness of the statistical model outputs, including consideration of conservative average particle emission factors with the lowest standard errors, narrowest 95% confidence intervals and largest sample sizes, and the explanatory model variables, which were *Vehicle Type* (all particle metrics), *Instrumentation* (particle number and $PM_{2.5}$), *Road Type* (PM_{10}) and *Size Range Measured* and *Speed Limit on the Road* (particle volume).

Discussion A multiplicity of factors need to be considered in determining emission factors that are suitable for modelling motor vehicle emissions, and this study derived a set of average emission factors suitable for quantifying motor vehicle tailpipe particle emissions in developed countries.

Conclusions The comprehensive set of tailpipe particle emission factors presented in this study for different vehicle and road type combinations enable the full size range of particles generated by fleets to be quantified, including ultrafine particles (measured in terms of particle number). These emission factors have particular application for regions which may have a lack of funding to undertake measurements, or insufficient measurement data upon which to derive emission factors for their region.

Recommendations and perspectives In urban areas motor vehicles continue to be a major source of particulate matter pollution and of ultrafine particles. It is critical that in order to manage this major pollution source methods are available to quantify the full size range of particles emitted for traffic modelling and health impact assessments.

Keywords: ANOVA; emission factors; linear regression; motor vehicles; multiple comparison,; particle mass; particle number; Scheffe; ultrafine particles.

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1 Background, aim, and scope

In urban areas motor vehicle fleets are the main source of particulate matter pollution, and these particles span a very broad size range (diameters 0.003–10 µm); however most are ultrafine size and measured in terms of particle number (number concentration of particles with diameters < 0.1 µm) (Harrison et al. 1999; Shi and Harrison 1999; Shi et al. 1999; Shi et al. 2001; Morawska 2003; Wahlin et al. 2001). For this reason, it is critical that particle number emissions be included in development of motor vehicle inventories and health impact assessments.

Emission factors are used in combination with transport data to develop inventories, and a very large body of data on emission factors derived from measurements is available in the international literature. These relate to measurement studies of vehicles under different driving conditions conducted on dynamometers in laboratories, on or near roads, and in tunnels. A wide range of different measurement methods have been used for different particle sizes, conducted in different parts of the world, and a multiplicity of issues need to be considered and resolved in order to derive emission factors. Factors can include vehicle type, fuel type, vehicle age, technologies fitted, speed and load, road environment characteristics, driving cycles, driving patterns, method and instrumentation used and size range measured, to name a few. This extensive body of data on particle emission factors has never been comprehensively analysed, and the question that remains is ***Which tailpipe particle emission factors are the most suitable to use in transport modelling and health impact assessments of motor vehicle fleets?***

Many mobile emission source models are available in developed countries which utilise performance-based emission factors (related to emissions generated per vehicle per kilometre derived from measurement data), for example, the average speed models MOBILE (USEPA 1993), EMFAC (CARB 2002), COPERT (Ahlvik et al. 1997; Ntziachristos et al. 2000; Bellasio et al. 2007); and VERSIT+ LD (Smit et al. 2007) which considers actual driving pattern data. Most of these models provide estimates for PM_{10}, and to a lesser extent $PM_{2.5}$. COPERT IV, however, has available a small suite of solid particle number emission factors for different vehicle types derived from dynamometer measurements (Samaras et al. 2005).

In developing countries access to land use and transport network data is often rare (Walker et al. 2008) and hence more indirect methods for estimating emissions are commonly used, such as basing emission factors on estimated total fuel consumed or on remotely sensed data. Emission estimates based on remotely sensed data usually provide a snapshot of emissions relating to a limited number of locations, and may not be representative of activity patterns for a typical trip in a region (Frey et al. 2002b); and the accuracy of fuel-based models can depend on how well the driving modes, vehicle and age distribution from which the emission factors were derived represent the study region (Frey et al. 2002 a,b).

The aim of this work was to identify the most suitable tailpipe particle emission factors to use in transport modelling and health impact assessments to quantify motor vehicle fleet particle emissions in terms of particle number, particle volume, PM_1, $PM_{2.5}$ and PM_{10} emissions, based on analysis of emission factors derived from measurement data. Emission factors for brake and tyre wear, road dust and particle surface area emissions were not considered in this analysis as only limited data exists in the literature.

2 Materials and methods

An extensive review was conducted of emission factors published in the international literature for particle number, particle volume, total particle mass, PM_1, $PM_{2.5}$ and PM_{10} for motor vehicle tailpipe emissions. Details of the literature reviewed and studies from which emission factor data was sourced for this study are outlined in Table 1. Based on this review, statistical models were developed and emission factor data classified and grouped into relevant sub-classes within each model variable class. Statistical model output data were analysed and a rationale developed to identify the most suitable average emission factors to use in modelling urban motor vehicle emissions.

2.1 Model variables examined

From an original population of over 900 emission factors reviewed in this study, the final emission factor sample size obtained was 667. This occurred due to the high number of missing data in the studies, as not all studies reported the same information. The model variables developed for the statistical analysis were based on data commonly reported in studies.

Data relating to a total of 667 particle emission factors were examined grouped into relevant sub-classes within each model variable class. The categorical model variables developed were *Particle Metric, Country of Study, Study Location, Instrumentation, Vehicle Type, Fuel Type, Road Type, Road Class;* and the continuous model variables were *Size Range Measured, Average Vehicle Speed, Speed Limit on the Road, Average Number of Vehicles travelling in a fleet per day, Drive Cycles, Engine Power, Heavy Duty Vehicle (HDV) Share, Number of HDVs travelling in a fleet per day.* These model variables are described in Table 2, and the sample size of emission factors relating to these model variables are shown in Table 3.

2.2 Statistical analysis of variables

We considered the relationship between reported tailpipe particle emission factors for different particle sizes to the various study-specific explanatory variables (Table 3) using linear models. In particular, the model for particle number (here denoted Y_i) in study i is related to Vehicle Type (j=1,2,3) and Instrumentation (k=1, …10):

$\hat{Y}_i = \beta_0 + \beta_{1j} + \beta_{2k}$ and $Y_i = \hat{Y}_i + e_i$

where β_0 is the intercept, β_{1j} is the effect of Vehicle Type j, and β_{2k} is the effect of Instrumentation k, and $e_i \sim N(0, \sigma^2)$. A similar model applies on changing the response (Y_i) with different explanatory variables (X_i).

A separate statistical model was developed for each of the six particle metrics examined in this study and the proportion of variation explained was calculated using $R^2 = 1 - \sum e_i^2 / \mathrm{Var}(Y_i)$. This is the fraction of variability in the dependent variable (the emission factor) that may be accounted for, or explained, by variation in the independent variable or variables, where the Var (Y_i) is the usual sample variance of Y_i.

In this study the analysis of the data for the categorical variables involved fitting a univariate general linear model (a multi-factor ANOVA). A stepwise technique, using both forward and backward elimination, was then used to select the best model. For the continuous variables linear regression analysis was undertaken with the variables added as independent explanatory covariates in the general linear model. All analysis was undertaken at a 5% level of significance. Statistically significant variables were identified through ANOVA tests and post-hoc Scheffe multiple comparisons (Scheffe, 1959). The multiple comparison statistical tests were conducted at a 95% confidence level for all categorical variables and their sub-classes to determine whether, within each class of categorical variable, there were statistically significant differences between the average published emission factor values for different sub-classes of variable.

Analyses were undertaken in SPSS (SPSS Version 14.0) and from these average particle emission factors for the different particle metrics, together with their standard error and 95% confidence interval values, were derived. A separate statistical model was developed for each of the six particle metrics examined in this study and model coefficients of determination derived (R^2), which provided information about the fraction of variability in the dependent variable (the emission factor) that may be accounted for, or explained, by variation in the independent variable or variables.

The statistical models produced average particle emission factors, and their associated standard error and 95% confidence intervals. The standard error value provides an indication of how reliable the model is as a means of predicting the average particle emission factor for the particular combination of values of the independent variables it relates to. The lower the standard error value, in relation to its associated average emission factor, the more reliable the predicted average emission factor may be considered. The lower and upper bound 95% confidence interval values produced by the statistical models for each average emission factor represent the range within which we can be 95% confident the true value will lie. In some statistical models combinations of dependent and independent variables produced high standard error values, and a lower bound 95% confidence interval value which, although physically uninterpretable, can be obtained as a consequence of the normal assumptions underlying the models, where these lower bound values were obtained they were not reported.

2.3 Basis for selection of the most suitable emission factors

The wide range of different capabilities of *Instrumentation* used to derive emission factors were not evaluated as an aim of this study. The rationale for selection of the most suitable tailpipe particle emission factors to use in transport modelling and health impact assessments from the five statistical model outputs was based on the statistical robustness of the statistical model outputs, including consideration of conservative average particle emission factors with the lowest standard errors, narrowest 95% confidence intervals and largest sample sizes. Other factors taken into account were the explanatory variables found for the statistical models. In considering the explanatory variable *Size Range Measured* the focus was on *Instrumentation* that measured the widest size ranges, including down to the lowest size range.

3 Results

This section presents the tailpipe particle emission factors considered the most suitable to use in transport modelling and health impact assessments.

3.1 Sample sizes of emission factors examined in the statistical models

All average emission factors predicted by the statistical models and presented in this paper are expressed in particle emissions generated per vehicle per kilometre driven. It is important to note when considering the sample sizes of emission factors examined in this study, that a single emission factor may represent one individual vehicle (or group of vehicles) tested on a dynamometer, or be the average emission factor derived for a vehicle type (eg., light duty vehicles) travelling in a vehicle fleet on a road or in a tunnel. Hence, the total sample size examined in this study of 667 emission factors represents a relatively very large sample of motor vehicles.

3.2 Statistical models developed to derive average emission factors

Six statistical models were proposed for particle number, particle volume, total particle mass, PM_1, $PM_{2.5}$ and PM_{10}. The analysis revealed that the statistical models developed for particle number, particle volume, PM_1 and $PM_{2.5}$ were robust, and explained 86%, 93%, 87% and 65% respectively of the variation in published emission factors. However the PM_{10} model was found to be less robust as it explained only 47% of the variation in published emission factor values. PM_{10} emission factors derived from studies conducted on or near roads may have been influenced by varying quantities of resuspended road dust occurring at the PM_{10} size range, leading to higher values than those derived from dynamometer and tunnel studies, and which may have confounded the ability of the statistical model to explain the variation in published emission factors.

The sixth statistical model for total particle mass was found to be a null model, as no explanatory variables were identified. This result is likely to be attributed to the fact that most of the studies simply measured total particle mass, and not different subsets of particle mass size fractions which typically have differing proportions of particle mass associated with them.

The final set of average tailpipe particle emission factors considered the most suitable for use in transport modelling and health impact assessments for different vehicle and road type combinations, together with their 95% confidence interval values, are presented in Table 4. Aspects related to their selection are discussed below.

4 Discussion

This section discusses the tailpipe particle emission factors considered the most suitable to use in transport modelling and health impact assessments for different particle metrics; and the results of statistical tests that examined differences in mean values of published emission factors.

4.1 Statistical models used to derive average emission factors

These are discussed below for different particle metrics.

***Particle number model*:** This statistical model explained 86% of the variation in published emission factors (n=156). *Vehicle Type* and *Instrumentation* were the explanatory model variables and emission factors were available for 10 different *Instrumentation*. In selecting the most suitable emission factors, it was important to consider *Instrumentation* that measured the lowest possible size range, including down to 0.003 µm where particle number emissions tend to be very prolific. This lower limit size range is commonly measured by the Condensation Particle Counter (CPC), which estimates particle count, and emission factors based on CPC measurements were available in the literature for Fleet, light duty vehicles (LDV) and heavy duty vehicles (HDV). However particle number emission factors for Diesel buses were restricted to those derived from Scanning Mobility Particle Sizer (SMPS) measurements.

The SMPS focuses on estimating particle size distribution (as opposed to total particle count) and does not measure the lower size range of the nucleation mode < 10 µm. The lower size window for the SMPS is commonly set higher than for the CPC, usually in the range 0.010-0.02 µm, whereas for the CPC the range is usually 0.002-0.01 µm, which means that generally the CPC measures the lower size range of the nucleation mode and the SMPS does not.

***Particle volume model*:** This statistical model explained 93% of the variation in published emission factors (n=57) and the explanatory model variables included *Vehicle Type*, *Speed Limit on the Road* and *Size Range Measured.* Consideration was given to selecting emission factors which related to the broadest size ranges measured, including down to the lowest possible size range, and to different reported *Speed Limits on the Road*. Most of the average particle volume emission factors, and their 95% confidence interval values, produced by the statistical model were less than 1 cm^3 per vehicle per kilometre. For almost all the particle volume emission factors *Speed Limit on the Road* or in the tunnel was reported, and the availability of this data may have contributed to the statistical model's high R^2 value of 0.93.

***PM_1 model*:** The explanatory variables for this statistical model were *Vehicle Type* and *Fuel Type,* which explained 87% of the variation in published emission factors (n=44). Emission factors examined in the analysis included those derived for diesel vehicles measured on a dynamometer; and from studies conducted on or near roads or in tunnels where the *Fuel Type* was not specified. The literature review revealed that at the time of this study the majority of LDVs were petrol-fuelled and HDVs diesel-fuelled, hence it can be assumed that these were the dominant *Fuel Types* in the vehicle fleets studied.

Few data are available in the literature for PM_1 emission factors, and given that most motor vehicle particle emissions are < 1 µm (dominated by ultrafine particles) this is an important size range to have a comprehensive database for. Recent research found that a combination of PM_1 and PM_{10} mass ambient air quality standards are likely to be more suitable to control combustion and mechanically-generated sources, such as motor vehicles, than the current standards of $PM_{2.5}$ and PM_{10} (Morawska et al. 2008), further emphasising the importance of deriving PM_1 emission factors.

***$PM_{2.5}$ model*:** Sixty-five percent of the variation in published emission factors (n=85) was explained by this statistical model, and its explanatory variables were *Vehicle Type* and *Instrumentation.* Emission factors were examined for 8 different *Instrumentation* reported in the literature.

***PM_{10} model*:** For PM_{10} the explanatory variables were *Vehicle Type* and *Road Type*, and this statistical model explained 47% of the variation in published emission factors (n=126). This low value for R^2 is reflected in the large values for standard errors (in relation to the predicted average emission factor) and high values for upper bound 95% confidence intervals produced by the statistical model. The presence of varying amounts of resuspended road dust at the PM_{10} size range are likely to have influenced emission factors derived in on-road studies, as compared to those derived from dynamometer and tunnel studies, and is likely to have confounded the explanation of variation. Few methods are available for discriminating road dust from tailpipe emissions, particularly at the $PM_{2.5}$ and PM_{10} size ranges, and quantities of road dust can vary depending on the construction material of road surfaces and their maintenance, climatic conditions, and other factors such as vehicle speed and traffic volumes.

Few bus emission factors are available derived from on-road measurements and those available and included in the statistical model related to measurements on boulevard and urban *Road Types* in the US (Abu-Allaban et al. 2003a). However the authors of this study considered their high PM_{10} emission factors were influenced by significantly high contributions from resuspended road dust and, within each vehicle category, by the effects of speed and acceleration (Abu-Allaban et al. 2003a). For this reason the average emission factor for buses derived from dynamometer measurements is also presented as a suitable emission factor in Table 4, in addition to average emission factors for bus for urban and boulevard *Road Types*, as it is considered more conservative and unlikely to be affected by high rates of resuspended road dust. This average dynamometer emission factor for bus included emission factors for a wide range of different urban bus *Drive Cycles*.

***Total particle mass model*:** No statistically significant variables were identified for this statistical model. The sample size was 199 and overall mean from this null model was 158 mg/km for all combined *Vehicle Types;* 158 mg/km for bus, and 91 mg/km for Fleet, 380 mg/km for heavy duty vehicles (HDV) and 32 mg/km for light duty vehicles (LDV). The inability to identify relationships in this statistical model may stem from the fact that these studies measured a broad range of different particle sizes, and most emission factors were not derived segregated by different subsets of particle mass fractions, but simply measured total particle mass.

4.2 Statistical differences between published emission factors

Post-hoc Scheffe's multiple comparison statistical tests (Scheffe 1959) were used to investigate the differences in means between levels corresponding to sub-classes within all categorical variables, irrespective of whether they had a significant effect on the response variable (the published emission factor value), at a 95% confidence level. The findings of these statistical tests are discussed below.

Country of Study; Study Location; Road Types vs Dynamometer: It was found that the variables *Country of Study* and *Study Location* (dynamometer, on or near the road, tunnel) were not statistically significant in explaining the variation in the means of published emission factors for most particle metrics. When comparing the means for different *Road Types* with those derived from dynamometer measurements, statistically significant differences were only found between dynamometer and motorway (PM_1) and dynamometer and boulevard *Road Types* (PM_{10}). These differences, however, are likely to have been influenced by high speed scenarios, as the PM_1 study measured emissions on a motorway in Switzerland with a speed limit of 120km/hr (Imhof et al, 2005a) and the PM_{10} study in the US attributed the significantly high PM_{10} emission rates to contributions from resuspended road dust and to the influence of variation in acceleration and speed (Abu-Allaban et al. 2003a).

Vehicle Type and ***Fuel Type:*** For *Vehicle Type* statistically significant differences were found between the means for Fleet and HDV for particle number, PM_1 and $PM_{2.5}$; and between the means for Fleet and LDV for $PM_{2.5}$. The means for LDV and HDV were found to be statistically significantly different for all particle metrics. No statistically significant differences were found between the means of different *Fuel Types* for particle number, or between the means for different *Fuel Types* for total particle mass. However statistically significant differences were found between the means for petrol and diesel *Fuel Types* for PM_{10}.

Instrumentation: No statistically significant differences were found between mean values measured by different *Instrumentation* for $PM_{2.5}$ and total particle mass. However, a significant difference was found between the mean value for published emission factors for particle number derived from the Condensation Particle Counter (CPC) of 22.69×10^{14} particles per vehicle per km and the Scanning Mobility Particle Sizer (SMPS) of 2.08×10^{14} particles per vehicle per km, highlighting a major difference between the results of these two measurement techniques, which requires investigation as a broader issue.

Statistically significant differences were found for PM_1 between the means for the Aerodynamic Particle Sizer (APS) and Betameter and between the APS and Beta-ray absorption monitors, however these differences are likely to be influenced by the fact that the PM_1 measurements related exclusively to diesel vehicles (LDVs and HDVs) tested on dynamometers in Australia. Higher values of emission factors are likely to be associated with diesel-fuelled vehicles as compared to petrol and other fuelled-vehicles.

Size Range Measured for particle number: In relation to the *Size Range Measured* for particle number, no statistically significant differences were found for the lower and upper size ranges measured for particle number between the average emission factors for the various levels of each of the categorical variables, after accounting for the associated variability of these estimates. Emission factors derived using the CPC for total particle count which reported only the lower size ranges measured (and did not report the upper size range measured) were unable to be included in these statistical tests. Their inclusion may have led to a different result as the CPC generally measures down to 0.002 µm, where particle numbers are very prolific.

4.3 Relevance and application of the average particle emission factors presented in this study

A general conclusion from examination of the results of the post-hoc multiple comparison tests discussed above is that these findings support the relevance and applicability of using the average emission factors derived in this study for modelling tailpipe particle emissions from urban fleets in developed countries. Where statistically significant differences were found these were generally associated with emission factors for diesel-fuelled vehicles, or related to high speed scenarios or to conditions with significantly high levels of resuspended road dust.

It is suggested that when using the average emission factors presented in this study, that three calculations be made. Firstly, a calculation using the relevant average emission factor, and two further calculations using the lower and upper bound 95% confidence interval values associated with the average emission factor (where available). It should be noted that where a single, individual road is concerned, the lower and upper bound 95% confidence interval values will be more widely distributed than those reported in this study.

5 Conclusions

This paper presents a comprehensive set of tailpipe particle emission factors, covering the full size range of particles emitted by motor vehicles, which are suitable for use in transport modelling and health impact assessments of urban fleet emissions in developed countries. These emission factors were derived for different *Vehicle* and *Road Type* combinations based on advanced statistical analysis of a large body of data on emission factors derived from measurement studies, and include emission factors for particle number and different fractions of particle mass.

The average emission factors were derived from statistical models which were found to explain 86%, 93%, 87% and 65% of the variation in published emission factors for particle number, particle volume, PM_1, and $PM_{2.5}$ respectively, and hence are concluded to have been derived from robust models. The statistical model for PM_{10}, however, explained only 47% of the variation in published emission factors and it is likely may have been confounded by the effects of resuspended road dust at this size range.

The explanatory variables identified in the statistical models included *Vehicle Type* (all particle metrics), *Instrumentation* (particle number and $PM_{2.5}$), *Fuel Type* (PM_1), *Road Type* (PM_{10}) and *Size Ranged Measured* and *Speed Limit on the Road (*particle volume), and we conclude that these are important variables to consider in design and interpretation of data in emission factor studies for different particle metrics.

The relevance and suitability of the derived set of tailpipe particle emission factors for use in urban areas in developed countries is supported by the findings from the statistical analysis of published emission factors in the international literature, which were as follows.

First, statistical analysis of published emission factors revealed that few statistically significant differences were found between the mean values for different particle metrics for *Country of Study* and *Study Location* (dynamometer, on or near a road, tunnel).

Second, few statistically significant differences were found between the means of published emission factors derived in dynamometer studies and those derived for different *Road Types*, except under high speed scenarios or conditions with significantly high levels of resuspended road dust, suggesting that for most particle metrics the two methods provide generally similar results.

Third, statistically significant differences were found between mean published emission factors for LDVs and HDVs for all particle metrics; and between petrol and diesel-fuelled vehicles for PM_{10}, consistent with higher emission rates that would be expected from diesel-fuelled vehicles, as compared to petrol and other fuelled vehicles.

6 Recommendations and perspectives

The average emission factors presented in this study are suitable for developing road-link based inventories, quantifying the spatial distribution of particle concentrations and for developing health impact assessments, covering the full size range of particles emitted by fleets. They are particularly useful for regions which may have insufficient funding to conduct measurements, or little or no data upon which to derive emission factors for their local region.

Better scientific techniques and tools are needed to produce data that can be used to model fleet emissions, as variations were found between different *Instrumentation* and methods used to derive emission factors. For example, statistically significant differences were found between the mean values of published emission factors for particle number measured by the Condensation Particle Counter of 22.69 x 10^{14} particles per vehicle per km, as compared to Scanning Mobility Particle Sizer (SMPS) *Instrumentation* of 2.08 x 10^{14} particles per vehicle per km, a difference which requires further investigation as a broader issue. Particle number emission factors for buses are rare and limited to estimates derived from SMPS measurements, which generally do not measure down to the lower size range of 0.002 μm in the nucleation mode where particle number tends to be very prolific.

While this study examined available tailpipe particle emission factors in the international literature, more studies are needed that derive speed-related particle emission factors for on-road and tunnel studies, particularly for speeds less than 50 km/hr to model congestion. More studies are also needed to derive emission factors for particle number for buses, and for different subsets of particle number < 1 μm, such as for ultrafine and nanoparticles (diameters < 0.05 μm), where particle number tends to be very prolific, for different *Vehicle Types*. Limited particle emission factor data are available for motor vehicles for particle volume, particle surface area, PM_1, brake and tyre wear, road grade, engine power, and for buses measured on different *Road Types*.

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Table 1 Source of tailpipe particle emission factors examined in the statistical analysis to derive average emission factors for different *Vehicle* and *Road Type* combinations

Table 2 Model variables examined in the statistical analysis to derive average emission factors to use in transport modelling and health impact assessments, to quantify tailpipe particle emissions generated by motor vehicle fleets

Table 3 Sample size of emission factors for different model variables examined in the statistical analysis, listed by particle metric

Table 4 Tailpipe particle emission factors for motor vehicles considered the most suitable to use in transport modelling and health impact assessments, derived based on advanced statistical analysis in this study of 667 emission factors in the international published literature

Table 1

Particle metric	*Researchers*	*Country of Study*	*Study Location* [e]	*Size Range Measured (nm)* [af]	*Instrumentation* [bd]	*Vehicle Type Emission Factors* [e]
Particle number	(Cadle et al, 2001)	USA	Dynamometer	> 3	ELPI, UCPC	LDV
	(CONCAWE, 1998)	Belgium	Dynamometer	10-237.2	DMA	LDV
				15.7-685.4	SMPS, DMPS	LDV
				10-1000	EAA	LDV
	(Morawska et al, 2001)	Australia	Dynamometer	15-700	SMPS	HDV
	(Ristovski et al, 2002)	Australia	Dynamometer	8-400	SMPS	Bus (Diesel)
	(Abu-Allaban, 2002)	USA	Tunnel	10-400	SMPS	Fleet
	(Gertler et al, 2002)	USA	Tunnel	10-500	SMPS	Fleet
	(Gidhagen et al, 2003)	Sweden	Tunnel	< 10, 10 -29, 29-109, 109-900, 3-900	DMPS	HDV, LDV
	(Imhof et al, 2005b)	Austria & UK	Tunnel	18-50, 18-100, 18-300, 18-700	SMPS	Fleet, HDV, LDV
	(Jamriska et al, 2004)	Australia	Tunnel	17-890	SMPS	Bus (Diesel)
	(Kristensson et al, 2004)	Sweden	Tunnel	3-900	DMPS	Fleet
	(Corsmeier et al, 2005)	Germany	Vicinity of the road	30-10,000	ELPI	Fleet, HDV, LDV
				3-900, 10-400	SMPS	Fleet
	(Gidhagen et al, 2004a)	Sweden	Vicinity of the road	7-450	CPC, DMPS	Fleet
	(Gidhagen et al, 2004b)	Sweden	Vicinity of the road	> 3	CPC, DMPS	HDV, LDV
	(Gramotnev et al, 2003)	Australia	Vicinity of the road	15-700	SMPS	Fleet
	(Gramotnev et al, 2004)	Australia	Vicinity of the road	14-710	SMPS	Fleet
	(Hueglin et al, 2006)	Switzerland	Vicinity of the road	7-3000	CPC	Fleet
	(Imhof et al, 2005c)	Germany	Vicinity of the road	30-10,000	ELPI	Fleet, HDV, LDV
	(Imhof et al, 2005a)	Switzerland	Vicinity of the road	> 7	CPC	Fleet, HDV, LDV
				18-50, 18-100, 18-300	SMPS	Fleet, HDV, LDV
	(Jamriska and Morawska, 2001)	Australia	Vicinity of the road	17-890	SMPS	Fleet
	(Jones and Harrison, 2006)	UK	Vicinity of the road	11-30, 30-100, 11-450, 101-450	SMPS	HDV, LDV
	(Ketzel et al, 2003)	Denmark	Vicinity of the road	10-700	CPC, DMPS	Fleet
	(Kittelson et al, 2004)	USA	Vicinity of the road	8-300	SMPS	Fleet
				3-1000	CPC	Fleet
	(Morawska et al, 2005)	Australia	Vicinity of the road	17-890	SMPS	Fleet, HDV, LDV
				700-20,000	APS	Fleet, HDV, LDV
	(Zhu and Hinds, 2005)	USA	Vicinity of the road	> 6	CPC	Fleet
Particle volume	(Imhof et al, 2005b)	Austria & UK	Tunnel	18-50, 18-100, 18-300, 18-700	SMPS	Fleet, HDV, LDV
	(Corsmeier et al, 2005)	Germany	Vicinity of the road	30-10,000	ELPI	HDV, LDV
	(Imhof et al, 2005c)	Germany	Vicinity of the road	29-250	ELPI	Fleet, HDV, LDV
				29-640, 29-1000	ELPI	Fleet
	(Imhof et al, 2005a)	Switzerland	Vicinity of the road	18-50, 18-100, 18-300	SMPS	Fleet, HDV, LDV
Total Particle mass	(Ayala et al, 2002)	USA	Dynamometer		MOUDI, ELPI, SMPS	Bus (Diesel & CNG)
	(Chatterjee et al, 2002)	USA	Dynamometer		not reported	Bus (Diesel)
	(Clark et al, 1997 & 1998)	USA	Dynamometer		not reported	Bus (Diesel & CNG)
	(Clark et al, 1999)	USA	Dynamometer		not reported	Bus (Diesel & CNG)
	(CONCAWE, 1998)	Belgium	Dynamometer	17.9-16,000	Berner impactor & filter paper	LDV
	(Kado et al, 2005)	USA	Dynamometer		not reported	Bus Diesel & CNG)
	(Lanni et al, 2003)	Canada	Dynamometer		Pallflex filters	Bus Diesel & CNG)
	(Lowell et al, 2003)	USA & Canada	Dynamometer		not reported	Bus(Diesel, CNG, LNG)
	(Morawska et al, 1998)	Australia	Dynamometer	8-300	SMPS	Bus Diesel
	(Bradley, 2000)	USA	Dynamometer		Fibreglass filters	Bus (Diesel, CNG, Hybrid)

Particle metric	*Researchers*	*Country of Study*	*Study Location* [e]	*Size Range Measured (nm)* [af]	*Instrumentation* [bd]	*Vehicle Type Emission Factors* [e]
Total Particle mass (c'td)	(SAE, 2001; 2002a,b; 2003a, b; cited in Lowell et al, 2003)	USA & Canada	Dnamometer		not reported	Bus (Diesel, CNG)
	(CARB, 2001; ARB's, 2002 cited in Lowell et al, 2003)	USA	Dynamometer		not reported	Bus (Diesel & CNG)
	(Ubanwa et al, 2003)	USA	Dynamometer		not reported	HDV, Bus (Diesel)
	(Wayne et al, 2004)	USA	Dynamometer		not reported	Bus (Diesel, LNG, Hybrid)
	(Jamriska et al, 2004)	Australia	Tunnel	17-700	SMPS	Bus (Diesel)
	(Holmen et al, 2005)	USA	Vicinity of the road		Telfon filters	Bus (Diesel), Hybrid Bus
	(Kittelson et al, 2004)	USA	Vicinity of the road	8-300	SMPS	Fleet
	(Mazzoleni et al, 2004)	USA	Vicinity of the road		Remote sensing	Fleet
	(Shah et al, 2004)	USA	Vicinity of the road		Teflon filters	Fleet, HDV
	(Zhang et al, 2005)	USA	Vicinity of the road	6-220	inverse modelling	HDV, LDV
				> 220*	inverse modelling	HDV, LDV
	(Abu-Allaban et al, 2003b)	USA	Vicinity of the road		Chemical balance	HDV, LDV
PM_1	(DOEH, 2003)	Australia	Dynamometer	sm	APS	HDV, LDV
	(Imhof et al, 2005b)	Austria & UK	Tunnel	sm	Kleinfiltergerate	Fleet, HDV, LDV
	(Gehrig et al, 2004)	Switzerland	Vicinity of the road	sm	Beta-ray	Fleet, HDV, LDV
	(Imhof et al, 2005a)	Switzerland	Vicinity of the road	sm	Betameter	Fleet, HDV, LDV
$PM_{2.5}$	(DOEH, 2003)	Australia	Dynamometer	sm	APS	HDV, LDV
	(Wayne et al, 2004)	USA	Dynamometer	sm	Glass-fibre filter	Bus (Diesel & LNG), Hybrid Bus
	(Gertler et al, 2002)	USA	Tunnel	sm	IMPROVE sampler	Fleet, HDV, LDV
	(Gillies et al, 2001)	USA	Tunnel	sm	Medium-volume samplers	Fleet
	(Imhof et al, 2005b)	UK	Tunnel	sm	TEOM	Fleet, HDV, LDV
	(Jamriska et al, 2004)	Australia	Tunnel	sm	TEOM, DustTrak	Bus (Diesel)
	(Kristensson et al, 2004)	Sweden	Tunnel	sm	TEOM & DMPS	Fleet
	(Tran et al, 2003)	Australia	Tunnel	sm	Teflon filters	HDV, LDV
	(Abu-Allaban et al, 2003a)	USA	Vicinity of the road	sm	DustTrak	HDV, LDV, Bus
	(Morawska et al, 2004)	Australia	Vicinity of the road	sm	DustTrak	Fleet
	(Abu-Allaban et al, 2003b)	USA	Vicinity of the road	sm	Chemical balance	HDV, LDV
PM_{10}	(Cadle et al, 1997)	USA	Dynamometer	sm	Teflon & Quartz filters	LDV
	(Cadle et al, 2001)	USA	Dynamometer	sm	MOUDI	LDV
	(Lowell et al, 2003)	USA & Canada	Dynamometer	sm	not reported	Bus (Diesel)
	(DOEH, 2003)	Australia	Dynamometer	sm	APS	HDV, LDV
	(Romilly, 1999)	UK	Dynamometer	sm	not reported	LDV, Bus, Midibus, Minibus
	(SAE, 2001; SAE, 2002a) cited in Lowell et al, 2003)	USA & Canada	Dynamometer	sm	not reported	Bus (Diesel & CNG)
	(Wayne et al, 2004)	USA	Dynamometer	sm	not reported	Bus (Diesel & LNG), Hybrid Bus
	(Gertler et al, 2002)	USA	Tunnel	sm	DustTrak	Fleet, HDV, LDV
	(Gillies et al, 2001)	USA	Tunnel	sm	Medium-volume samplers	Fleet
	(Hibberd, 2005)	Australia	Tunnel	sm	Statistical analysis [c]	Fleet, HDV, LDV
	(Imhof et al, 2005b)	Austria	Tunnel	sm	TEOM	Fleet, HDV
	(Kristensson et al, 2004)	Sweden	Tunnel	sm	TEOM & DMPS	Fleet
	(Schmid et al, 2001)	Austria	Tunnel	sm	Quartz filters	Fleet, HDV, LDV
	(Tran et al, 2003)	Australia	Tunnel	sm	Teflon filters	LDV
	(Abu-Allaban et al, 2003a)	USA	Vicinity of the road	sm	DustTrak	HDV, LDV, Bus
	(Venkatram et al, 1999)	USA	Vicinity of the road	sm	Teflon filters	Fleet
	(Gehrig et al, 2004)	Switzerland	Vicinity of the road	sm	Beta-ray	Fleet, HDV, LDV
	(Imhof et al, 2005a)	Switzerland	Vicinity of the road	sm	Betameter	Fleet, HDV, LDV

[a] 1000 nm is equivalent to 1 µm. These units refer to particle diameter. [b] *Instrumentation* (in alphabetical order) - Aerodynamic Particle Sizer (APS), Berner low pressure Impactor, Beta-ray absorption monitors, Betameter, Chemical Mass Balance, Condensation Particle Counter (CPC), Differential Mobility Analyzer (DMA), Differential Mobility Particle Sizer (DMPS), Dynamometer, DustTrak, Electrical Aerosol Analyser (EAA), Electrical Low Pressure Impactor (ELPI), Filters (Fibreglass, Glass fibre, Teflon, Quartz), Kleinfiltergerate, LIDAR-based VERSS and remote sensing, Mass Single Stage Multidilutor, MOUDI (Micro-Orifice Uniform Deposit Impactor), Samplers (IMPROVE, high volume, medium volume), Scanning Mobility Particle Sizer (SMPS), Tapered Element Oscillating Microbalances(TEOM) and Ultrafine Condensation Particle Counter (UCPC). [c] Fit log-normal functions to extrapolate concentrations beyond > 220nm. Statistical analysis of in-stack pollution monitoring data and hourly vehicle counts. [d] Not reported – dynamometer studies which did not provide further information on *Instrumentation* used. [e] Vicinity of the road studies refer to studies conducted on or near the road, near a kerb, upwind or downwind of the road. [f] sm – refers to *Size Range Measured* and relates to particles with diameters < 1 µm, < 2.5 µm and < 10 µm (known as PM_1, $PM_{2.5}$ and PM_{10} respectively). [g] LDV (Light duty vehicles), HDV (Heavy duty vehicles) – refer Table 2 for further detail.

Table 2

Model Variable Name	Model Variable Sub-classes
Particle Metric	Particle number, particle volume, total particle mass, PM_1, $PM_{2.5,}$ PM_{10}
Country of Study	Australia; USA/Canada; Other Countries (Austria, Belgium, Denmark, Germany, Sweden, Switzerland, UK) [a]
Study Location	Dynamometer (in a laboratory), tunnel or in the vicinity of a road [b]
Road Type	Boulevard, freeway, highway, motorway, rural area, tunnel, urban [c]
Speed Limit on the Road	The reported *Speed Limit on the Road* [d]
Road Class	Urban and Non-Urban roads; Highway and Non-Highways roads [e]
Average Number of Vehicles Per Day	The average number of vehicles travelling in a vehicle fleet per day [f]
Heavy Duty Vehicle Share	Percentage of heavy duty vehicles (HDVs)travelling in a vehicle fleet per day [g]
Number of HDVs Per Day	Number of HDVs travelling in a vehicle fleet per day [h]
Vehicle Type	Fleet, light duty vehicles (LDVs), heavy duty vehicles (HDVs) Bus [i]
Fuel Types	Diesel, Gasoline, Compressed Natural Gas, Liquefied Natural Gas [j]
Drive Cycles	*Drive Cycles* for Buses, Trucks and Other vehicles [k]
Average Vehicle Speed	*Average Vehicle Speed* tested on a dynamometer or reported in a tunnel or vicinity of the road study
Engine Power	Reported for two bus studies [m]
Instrumentation	20 different types of *Instrumentation* [n]
Size Range Measured	*Size Range Measured* by *Instrumentation* [o]

[a] Groups based on numbers of studies found. [b] Vicinity of the road - on or near the road, near a curb, upwind, downwind or a road. [c] Urban *Drive Cycle* data classed as urban *Road Type*. [d] Few studies reported, where reported was Boulevard 82, highway 82 and 100, freeway 100, motorway 120, tunnel 60, 64, 80, 89, urban 50 and 57 km/hr. [e] Road Class based on either the reported *Speed Limit on the Road*, or the speed limit that would most likely be associated with the *Road Type.* < 60 road classed Urban; ≥ 60 non-Urban; ≥ 80 Highway; < 80 km/hr non-Highway. Insufficient data were available to examine individual speeds or other specific speed ranges. [f] Ranges 13,128-103,080 per day particle number; 23,000-30,000 particle volume; 12,540-12,900 total particle mass; 20,000-69,816 PM_1; 20,000-69,816 per day PM_{10}. 5 buses/minute particle number and $PM_{2.5}$. [g] Ranges 5-100% particle number, 7-60% particle volume; 1-100% total particle mass, $PM_{2.5}$; 6.1-18% PM_1; 2.6-83% for PM_{10}. [h] Derived where data for both *Average Number of Vehicles Per Day* and *Heavy Duty Vehicle Share* (%) were available. [i] Based on author classifications, including HDV (number of axles, gross vehicle mass weight or length); LDV (wheel pair distance, vehicle length or weight). LDVs included cars and trucks with specified vehicle weights; and HDVs with gross vehicle mass weights ranging from 3.5-12 tonne to > 25 tonne. [j] Few reported diesel fuel sulphur content, where reported was < 15ppm, < 30 ppm Ultralow sulphur diesel (ULSD) HDV; 300ppm Low sulphur diesel (LSD) for Bus, 24-480ppm for LDV and HDV. Diesel, ULSD and LSD classed as diesel *Fuel Type.* [k] Buses - Bus Route, Central Bus District, Central Business District – Aggressive Driving, Composite, CUEDC cycle, Manhattan, New

York Bus, Orange County Transit Authority, Route 22, Route 77, UDDS and Urban. Other vehicles - CUEDC cycle, FTP, HHDDT; Hot UC, Hot Cycle, Cold Cycle, REP05, Steady State, UC and Urban. Trucks - CBD–CBD14, HDCC. [l] Ranges < 50, 50-120 particle number, 86-113 particle volume; 80-120 total particle mass; 30-90 PM_1; 45-91 $PM_{2.5}$; < 65 and 45-91 km/hr for $PM_{10.}$ [m] *Engine Power:* Reported in two diesel bus studies (Jamriska et al. 2004; Ristovski et al. 2002). [n] Instrumentation (in alphabetical order) Aerodynamic Particle Sizer, Berner low pressure Impactor, Betameter, Beta-ray absorption monitors, Chemical Mass Balance, Condensation Particle Counter , Differential Mobility Analyzer, Differential Mobility Particle Sizer, DustTrak, Electrical Aerosol Analyser, Electrical Low Pressure Impactor, Filters (Fibreglass, Glass fibre, Teflon, Quartz), Kleinfiltergerate, LIDAR-based VERSS and remote sensing, Mass Single Stage Multidilutor, Micro-Orifice Uniform Deposit Impactor, Samplers, Scanning Mobility Particle Sizer, Tapered Element Oscillating Microbalances, Ultrafine Condensation Particle Counter. [o] Particle number 0.003-1 µm (dynamometer), 0.01-0.9 µm (tunnel), 0.003-20 µm (vicinity of the road); particle volume 0.018-10 µm. Ranges particle number 0.003-1 µm (dynamometer), 0.01-0.9 µm (tunnel studies), 0.003-20 µm (vicinity of the road), total particle number count > 3 nm; 0.018-10 µm (particle volume). Few size ranges reported in total particle mass studies, where reported 0.008-16 µm (dynamometer), 0.017-0.7 µm (tunnel), 0.008-0.3 µm, > 0.22 µm vicinity of the road.

Table 3

Sample sizes related to Study Location and Road Environment statistical model variables

Particle metric	***Country of Study*** [a]			***Study Location***			***Road Type***	***Speed Limit***	***Road Class km/hr***		***Road Class km/hr***		***Average No Vehicles per day*** [d]	***HDV Share, %*** [d]
	Australia	Other [b]	USA & Canada	Dyno	Tunnel	Vicinity of road			≤ 60	> 60	< 80	≥ 80	On-road fleets	On-road fleets
P Number	26	109	21	15	50	91	149	99	36	114	48	102	104	100
P Volume	--	57	--	--	23	34	57	55	9	48	21	36	52	28
PM_1	10	34	--	10	9	25	34	15	11	31	30	12	34	25
$PM_{2.5}$	18	7	60	17	18	50	72 [c]	20	26	52	31	38	7	38
PM_{10}	19	50	57	45	23	58	96 [c]	33	58	31	47	40	38	54
Total Mass	3	12	184	165	2	32	119 [c]	8	97	65	97	65	2	18
TOTAL	76	269	322	252	125	290	240	230	237	341	274	293	237	263

Sample sizes related to Vehicle Type and Instrumentation statistical model variables

Particle metric	***Vehicle Type***	***Fuel Type Reported*** [e]	***Drive Cycle***	***Average Vehicle Speed***	***Engine Power***	***Instrumentation***	***Size Range Measured*** [g]
P Number	156	34	6	13	2	156	156 (lower) [f]; 137(upper)
P Volume	57	--	--	2	--	57	57 (lower & upper)
PM_1	44	16	17	16	--	44	Particles with diameters < 1 µm
$PM_{2.5}$	85	33	17	26	4	85	Particles with diameters < 2.5 µm
PM_{10}	126	37	31	14	nr	126	Particles with diameters < 10 µm
Total Mass	199	173	150	17	2	199	15 (lower & upper)
TOTAL	667	293	221	88	8	667	232 (lower) [f]; 207 (upper)

[a] *Country of Study* is considered to have limited relevance for dynamometer measurements, except for Urban *Drive Cycles,* which were classed Urban *Road Type* (see [c] below). [b] Other Countries included studies from Austria, Belgium, Denmark, Germany, Sweden, Switzerland and the United Kingdom. [c] Within these total *Road Type* sample sizes, 92 emission factors related to total particle mass, 16 to $PM_{2.5}$ and 23 to PM_{10} which were dynamometer measurements using an Urban *Drive Cycle*. These data were classified in the statistical models as Urban *Road Type.* [d] *Average Number of Vehicles Per Day* and *Heavy Duty Vehicle Share* sample sizes related to on-road vehicle fleets, and where data was available in studies for both these variables, the additional model variable *Number of HDVs Per Day* was derived. [e] Not all studies reported vehicle *Fuel Type*, particularly studies of on-road vehicle fleets. [f] Some particle number studies reported only the lower *Size Range Measured*, such as where total particle count was measured. Lower & upper – represent the lower size range and upper size ranges measured.

Table 4

Particle metric	Emission unit per vehicle	Explanatory variables (in bold italics)	Fleet	95% CI	HDV	95% CI	LDV	95% CI	Bus	95% CI
			Emission Factors and their 95% confidence intervals (CI)							
Particle number	10^{14} particles per km	***Vehicle Type & Instrumentation***								
		CPC [c]	7.26	3.85-10.66	65	60.19-69.81	3.63	[a]-9.85	--	--
		SMPS [c]	--	--	--	--	--	--	3.08[b]	[a]-9.30
Particle volume	Cubic cm per km	***Vehicle Type, Size Range Measured & Speed Limit on the Road***								
		18-300nm, <= 60 km/hr	0.07	[a]-0.19	0.93	0.81-1.06	0.03	[a]-0.15	--	--
		18-700nm, > 60 km/hr	0.04	[a]-0.16	0.41	0.32-0.49	0.05	[a]-0.3	--	--
PM_1	mg per km	***Vehicle Type & Fuel Type***								
		Fuel not specified	36	2-70	--	--	16	[a]-50	--	--
		Fuel not specified & diesel Combined	--	--	287	257-317	--	--	--	--
$PM_{2.5}$	mg per km	***Vehicle Type & Instrumentation***								
		TEOM & DMPS [c]	60	[a]-166	--	--	--	--	--	--
		DustTrak	--	--	--	--	33	[a]-80	299[b]	205-394
		All Instrumentation	--	--	302	236-367	--	--	--	--
PM_{10}	mg per km	***Vehicle Type & Road Type***								
		Boulevard	--	--	4815	3459-6171	454	[a]-1413	4130[ce]	2774-5486
		Urban	688	[a]-1546	538	[a]-1145	156	[a]-635	1089[ce]	306-1872
		Freeway	200	[a]-2118	2500	1144-3856	285	[a]-1244	--	--
		Highway	66	[a]-1421	840	[a]-1947	141	[a]-924	--	--
		Motorway	77	[a]-1432	213	[a]-1568	63	[a]-1419	--	--
		Rural Area	67	[a]-1984	394	[a]-2312	46	[a]-1964	--	--
		Tunnel	306	[a]-884	1019	236-1802	14	a- 797	--	--
		Dynamometer [e]	--	--	--	--	--	--	313[ce]	[a]-753

[a] The lower bound 95% confidence interval value calculated to be negative and therefore is not valid. These values, although physically uninterpretable, can be obtained as a consequence of the normal assumptions underlying the models, and hence are not reported. [b] Diesel buses. [c] Buses – Fuel not specified (can be assumed to be Diesel-fuelled due to the timing and location of the studies), principally Diesel-fuelled buses. [d] Condensation Particle Counter (CPC), Scanning Mobility Particle Sizer (SMPS), Tapered Element Oscillating Microbalances (TEOM) and Differential Mobility Analyzer (DMA). [e] The average dynamometer emission factor for buses for PM_{10} is also presented; as the on-road boulevard and urban *Road Type* studies were reported to be affected by very high levels of resuspended road dust and the influence of variation in acceleration and speed (Abu-Allaban et al. 2003a).