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Jamriska, Milan, Morawska, Lidia, Thomas, Stephen, & He, Congrong
(2004) Diesel Bus Emissions Measured in a Tunnel Study.
Environmental Science and Technology, *38*(24), pp. 6701-6709.

Diesel Bus Emissions Measured in a Tunnel Study

Milan Jamriska,* Lidia Morawska, Steven Thomas, and Congrong He

International Laboratory for Air Quality and Health, School of Physical and Chemical Sciences, Queensland University of Technology, 2 George Street, Brisbane, Queensland 4001 Australia

Abstract:

The emission factors of a bus fleet consisting of approximately 300 diesel-powered buses were measured in a tunnel study under well-controlled conditions during a 2-d monitoring campaign in Brisbane. Particle number and mass concentration levels of submicrometer particles and $PM_{2.5}$ were monitored by SMPS and DustTrak instruments at the tunnel's entrance and exit, respectively. Correlation between DustTrak and TEOM response to diesel emissions was assessed, and the DustTrak results were recalculated into TEOM equivalent data. The mean value of the number and mass emission factors was $(3.11\pm2.41) \times 10^{14}$ particles km^{-1} for submicrometer particles and 583 ± 451 mg km^{-1} for $PM_{2.5}$ (DustTrak), respectively. TEOM $PM_{2.5}$ equivalent emission factor was 267 ± 207 mg km^{-1}. The results are in good agreement with the emission factors determined from steady-state dynamometer testing of 12 buses from the same Brisbane City bus fleet. The results indicate that when carefully designed, both approaches, the dynamometer and on-road studies, can provide comparable results, applicable for the assessment of the effect of traffic emissions on airborne particle pollution. A brief overview of emission factors determined from other on-road and dynamometer studies reported in the literature as well as with the regulatory values used for the vehicle emission inventory assessment is presented and compared with the results obtained in this study.

Introduction

Knowledge of vehicle emission factors is essential for developing emission inventories, for modeling of various air pollution and emission characteristics, and for planning of traffic and transport growth with a view to minimize its impact on human health and the environment. An emission factor is typically defined as the amount of a chemical species emitted per unit mass of fuel burned (mass-based emission factor) or per a defined task performed (task-based emission factor). Vehicle emissions are commonly expressed as task-based emission factor, with the task being a distance driven by a vehicle (g/km) or per work done (g/kWh).

There are a number of methods available for determi nation of vehicle emission factors. The one that is most commonly used, and which has been included in many national standard emission-testing procedures, is by measuring of emissions of a vehicle driven on a dynamometer through a certain driving cycle. Controllability of the testing conditions and the resulting comparability of the values derived are the main advantages of the method; however, its serious limitations are the costs and the complexity. These limitations mean that often only a small number of vehicles are tested, unrepresentative of the overall composition of the vehicle fleet on the roads. Additionally, dynamometer conditions are not necessarily representative of real road

conditions. An alternative way for determination of vehicle emission factors is by measuring of the pollutant concentra tions in very close proximity to a road (above the road, at a curbside, or in a tunnel) as well as monitoring of the vehicle traffic on the road and calculating the factors using these experimental data and an appropriate model. The main advantage of this method is that the derived emission factors are more representative of the whole fleet composition, but its serious limitation being the limited control over the conditions of the measurements, both in terms of meteorological conditions affecting the measured concentrations and vehicle fleet mix on the road. It is thus usually very difficult to estimate the emission factors of individual classes of vehicles (for example, gasoline driven vs diesel or diesel buses vs trucks). This method is not included in any standard testing procedures.

To partially overcome the limitations presented by each of these two approaches, there are currently new methods emerging that combine some elements of both. An example is sampling of emissions from a vehicle moving on the road by instrumentation placed onboard of another vehicle, which is following the one being tested (*1*). Such methods are still in the early stages of development. Despite the limitations, and in the absence of a "perfect" method for measuring vehicle emission factors, the two main methods will continue to be used. An improvement in the reliability of the results obtained using these two methods can be obtained through (i) increasing the number of on-road studies and conducting them for conditions as best controlled and defined as possible and (ii) comparing the results obtained by these two methods for the same vehicle fleet, which means conducting comprehensive dynamometer and road studies in the same city for the same sample of vehicles.

The second point is particularly important because to date the major dynamometer and road studies were conducted in different locations, and thus meaningful comparison of the results is rarely possible. Availability of comparative results would significantly contribute toward developing quantitative understanding of the trends and biases related to each of the two methods. The purpose of this work is (i) to determine the bus emission factors through a well-controlled road study and (ii) to compare the emission factors obtained from the road measurements in the first instance with the dynamometer studies conducted in Brisbane and second with the emission factors reported in the literature. A specific focus was on submicrometer particles and $PM_{2.5}$ (particles with aerodynamic diameter smaller than 2.5 μm).

Through a number of projects conducted in the past few years, we have accumulated a body of data on emission factors of diesel buses operating in the city of Brisbane, Australia. The emission factors were measured through steady-state dynamometer testing. The results of dynamometer studies are compared with emission factors determined from the on-road measurements, presented in this study.

A particularly good opportunity arrived with the opening of a tunnel in the inner city of Brisbane for restricted use by the city buses. Shortly after the opening, the tunnel was used by buses delivering fans to a major sport event extending over a period of a few days. Each evening a relatively large number of buses travelled through the tunnel to deliver people to the event, and about 2 h later, to take them back to the center of the city. This way the conditions for testing were as best controlled as practically possible: a large traffic fleet of Brisbane City buses, of the same type, using the same fuel, and maintained by the same garage, as those that were previously tested through the dynamometer studies.

Experimental Section

The measurements were conducted over 2 days, starting at 16:30 and finishing about 22:30 each day. This corresponded to the time when buses were taking people from the city to a sporting event starting at 19:00 and continuing for approximately 2 h. The measurements commenced every day before the bus traffic started building up and continued for some period after it completely ceased. The measurements for no traffic in the tunnel were conducted to determine the background characteristics in the tunnel. The measurements of number concentration for submicrometer particles and mass concentration for $PM_{2.5}$ were conducted at both ends of the tunnel, with the instrumentation located above the tunnel gates and the sampling tubes for the instrumentation extending by about 1 m below the ceiling of the tunnel.

Tunnel Description. The study was conducted in the Woolloongabba Tunnel, which is a part of a newly built busway. It is located in the inner Brisbane City urban area, approximately 3 km from the CBD. The tunnel is 511 m long, almost straight with slightly curved descending and ascending sections at both ends. The middle section of a length of approximately 300 m is horizontal. The cross sectional area of the tunnel is 60 m^2 and is constant throughout its whole length. The tunnel carries two-way traffic, one lane in each direction, with a speed limit of 60 km h^{-1}. The traffic carried by the urban streets in the vicinity of the tunnel's ends could be considered as medium to low.

The airflow induced by the fans is one-directional with the buses travelling through the tunnel providing additional air movement and mixing. The ventilation is provided by a system of fans moving the air from the south end (entrance) to the north end (exit) of the tunnel. The three sets of fans are located in the middle of the tunnel and approximately 150 m away from the entrance and exit. Each set consists of three fan units mounted across the tunnels ceiling suspended approximately 1 m down from the top. The number of fans operating at each instant and the choice of specific fan units is determined by PLC (Programmable Logic Control) and SCADA (System Control And Data Acquisition) systems using the concentration levels of CO, CO_2, and NO_x and air visibility as the input parameters. These are measured by 10 sets of sensors spread evenly throughout the length of the tunnel with readings provided every second. For most of the time during the measurements, the number of fans operating ranged from two to four.

Instrumentation. The instrumentation used in the study included: two scanning mobility particles sizers (SMPS) for determination of particle size distribution (PSD) and concentration levels in the submicrometer size range, two DustTrak units, and a TEOM for determination of $PM_{2.5}$ concentrations.

The two SMPSs consisted of the Electrostatic Classifiers (EC TSI model 3071A) and condensation particle counters (CPC TSI models 3010 and 3022), respectively. SMPS operates on a principle of particle classification by the EC according to their electrical mobility, which is a function of their size, followed by particle counting by the CPC, which utilizes laser light scattering. The whole process is automated and software controlled. Particle size range of 0.017-0.7 μm and a time resolution of 5 min were selected as the operating parameters for both instruments in this study.

The TSI model 8520 DustTrak is a laser photometer with a sensing mechanism consisting of a laser diode, which is directed at aerosol present in a continuous

ambient airflow induced through the instrument. The amount of light measured by the photodetector is converted by the internal electronics to the mass concentration by means of a proportionality constant. The manufacturer determines the proportionality constant by calibration of the instrument against the ISO 12103-1 gravimetric measurement with A1 test dust (Arizona test dust).

Both DustTrak units operated with a 2.5 μm impaction inlet (50% cutoff efficiency for particles larger than 2.5 μm) and a time resolution of 1 min. One of the units was calibrated: (a) for ambient air dominated by traffic emissions measured nearby a busy freeway carrying both gasoline and diesel engine vehicles; (b) at the bus tunnel under the test conditions as encountered during the measuring campaign, by running it side by side with a tapered element oscillating microbalance (TEOM). The TEOM is certified by the U.S. EPA as an equivalent to gravimetric techniques for PM_{10} and $PM_{2.5}$ measurements in ambient air. An inlet head with 2.5 μm cutoff was used in the study for TEOM measurements. The time resolution used for the DustTrak/TEOM comparison assessment was 5 min, and operational temperature for TEOM was 50 $^{\circ}$ C. The instrument noise level for the selected sampling interval and the concentration levels encountered in the study was estimated at 2-5 μg m^{-3} with the larger error associated with the lower particle concentration levels.

Both SMPSs were calibrated in the laboratory before the field measurements for the PSD using standard latex spheres and inter-compared for particle concentration readings using diesel-dominated urban ambient air (R^2 = 0.95). The two DustTrak units were also inter-compared using the same test conditions as for the SMPSs and showed good correlation (R^2 > 0.95). More details on comparison of DustTrak, TEOM, and other real-time instruments for airborne particulate matter monitoring can be found for example in refs *2* and *3*.

Study Design. The concentration of particle number and $PM_{2.5}$ was measured continuously at the tunnel's entrance and exit. The instrumentation at both ends was located on top of the tunnel gates, with air sampled via two identical sampling tubes 3 m long and of 0.01 m internal diameter. The sampling points were 1 m below the tunnel's ceiling. The effect of particle losses in sampling lines of such length and diameter was evaluated experimentally and theoretically *(4)* and found to be negligible.

Traffic was monitored by visual recording of the number of buses travelling in and out of the tunnel in 1-min intervals. The traffic flow rate at its peak was approximately 5 buses min^{-1}. The bus fleet characteristics were estimated from the data available for the bus fleet population from which the tested sub-fleet was selected. The data provided by the bus fleet operator are presented in Table 1. All buses were powered by diesel engines of which 84% complied with the ECE R-49, 6% with Euro I, and 10% with Euro II emission standards. The age and mileage distribution was very broad, with average values between 1 and 13 yr and 0.7×10^5 to 7.5×10^5 km, respectively. The weighted average values were 10.3 yr and 5.97×10^5 km. The mileage estimates were calculated from the average age and the annul mileage average of 5.8×10^4 km yr^{-1}.

Table 1. Bus Fleet Characteristics[a]						
		age (yr)			mileage[c] (km)	
bus category[b]	fraction (%)	avg	STD	range	avg	range
Euro I diesel	6.1	4	2	1-6	2.32×10^5	$(0.58\text{-}3.48) \times 10^5$
Euro II diesel	9.7	1.3	1	0-2	7.54×10^4	$(0.01\text{-}1.16) \times 10^5$
R49 diesel	21.2	8.2	4	4-12	4.76×10^5	$(2.32\text{-}6.96) \times 10^5$
R49 diesel	63.0	13	4	9-20	7.54×10^5	$(0.52\text{-}1.16) \times 10^6$

[a] Based on the characteristics for the overall bus fleet population ($n = 638$) from which the tested buses were pooled. [b] Compliant with the listed emission standards. [c] Estimated from average age and annual mileage (5.8×10^4 km/yr).

Air velocity in the tunnel was measured by two sampling hot-wire anemometers located inside of the tunnel, approximately 50 m from the entrance and exit, providing readings every second. The probes were mounted approximately 1 m from the ceiling and were part of the PLC and SCADA systems as described previously. An average (mean) value of the velocities from both probes was used for emission factors calculation. Since the hot-wire anemometers measure air speed (scalar value) rather than velocity (vector), the measured data may overestimate the average axial air velocity; however, the effect was not considered in the presented study. The problem is in detail discussed by Pierson et al. (5) in their review of the Van Nuys 1987 tunnel study.

Determination of Emission Factors. Particle number and mass emission factors (NEF, MEF) were calculated from the formula (6, 7):

$$EF = \frac{(C_{exit} - C_{entrance})v_{air}S}{LN} \qquad (1)$$

where C_{exit} and $C_{entrance}$ are particle number or mass concentration measured at the tunnel's exit and entrance, respectively; v_{air} is the mean value of air velocity in the tunnel; S and L are the tunnel's cross-section area and length; and N is traffic flow rate.

Data processing and emission factor calculations were conducted in the following steps:

(i) Time series of measured data (i.e., number and mass concentration, air velocity, and traffic flow rate) were loaded into a spreadsheet and aligned according to time of measurements.

(ii) The time scale was divided into consecutive 1- (DustTrak data) and 5-min (SMPS data) intervals.

(iii) For each time interval, a mean value (arithmetic average) of air velocity, traffic flow rate, and particle concentration was calculated and assigned to a midpoint of the

time interval. The intervals for which one or more values were missing or the traffic or air flow rate was zero were excluded.

(iv) Emission factors were calculated according to eq 1. The results were screened for outliers using boxplot and their effect on mean values assessed by t-test. Less than 5% of data were outliers, all of the highest rank. The difference between means for data including and excluding the outliers was at 5% significance level ($p = 0.05$) insignificant (p-values 0.34 and 0.22 for NEF and MEF, respectively). In order not to exclude high emitters from the tested bus fleet, all data were included in analysis. A complete set of data used in the study as well as descriptive statistics for calculated number and mass emission factors are presented in the Supporting Information.

(v) Mean of the EF values was calculated, and data variability were assessed by standard deviation (STD).

(vi) Median of the EF values was calculated, and data variability were assessed using semi-quartile range (Q) calculated as: $Q = (Q3 - Q1)/2$, where $Q1$ and $Q3$ are the first (25%) and the third (75%) quartiles of calculated EF values, respectively. The quartiles were determined from histogram (frequency) of EF values segmented into 10 consecutive equally large intervals.

Since the histogram of calculated EF values showed a positively skewed normal distribution, the median value may be considered as a more representative measure of the central tendency of EF derived in this study. On the other hand, most of the results from similar studies found in the literature report only the mean value. For these reasons both mean and median values of emission factors for particle number and mass in submicrometer size range and mass emission factors for $PM_{2.5}$ are presented here.

Relationship between DustTrak and TEOM. While measurement of diesel vehicle particle emissions is commonly accomplished using Code of Federal Regulations (CFR) (8) defined filter collection methods of exhaust sampled from a dilution tunnel, use of other methods such as TEOM or optical instruments is also applicable and offers several advantages. Application of TEOM has obtained the status of automated equivalent method to the US Federal Reference Method. The TEOM excels in the area of constant calibration, independent of vehicle and offers relatively good time resolution. The disadvantage of TEOM application for vehicle emissions studies are losses of a fraction of semi-volatile materials during sampling, resulting in an underestimation of true mass (2, 9).

Optical instruments, such as DustTrak, provide near real-time results, high signal-to-noise ratio, freedom from interference due to other exhaust sample properties, and simplicity. On the other hand, the calibration process is however critical since the DustTrak's response may vary for different types of measured aerosol (9).

Since only one TEOM instrument was available for this project, the mass emission factors for $PM_{2.5}$ were determined by DustTrak. Two DustTrak units were used to monitor $PM_{2.5}$ concentration ($PM_{2.5DustTrak}$) at the tunnel's entrance and exit. The readings were then recalculated into TEOM equivalent data from a known relationship between DustTrak and TEOM response.

Prior to the field measurements, one DustTrak unit was calibrated against TEOM using traffic emissions' dominated ambient air as the test aerosol. The emissions in this case were attributed to both gasoline and diesel engine vehicles, which in terms of DustTrak response may differ compared to diesel-only emissions. Since aerosol of different origin may have different chemical and optical properties, a second round of calibration was conducted in the bus tunnel after the completion of the field measurements.

The results are presented in Figure 1. The TEOM and DustTrak data was well correlated ($R^2 = 0.75$ for diesel-only and $R^2 = 0.91$ gasoline and diesel emissions) over the whole concentration range of up to 90-130 μg m^{-3}, which as presented later, covers the levels encountered in the tunnel measurements. The second DustTrak was inter-compared with the first DustTrak by sampling side-by-side traffic emissions-dominated urban ambient air over a period of 5 h and showed very good correlation ($R^2 = 0.95$). The relationship between $PM_{2.5}$ concentration measured by DustTrak ($PM_{2.5DustTrak}$) and TEOM equivalent ($PM_{2.5TEOM}$) was estimated using the calibration for diesel-only emissions as:

$$PM_{2.5TEOM} = 0.458 PM_{2.5DustTrak} + 4.882 \; (\mu g \, m^{-3}) \quad (2)$$

The values of mass emission factor for $PM_{2.5}$ TEOM equivalent (MEF_{TEOM}) were calculated from eq 1, using concentration values $PM_{2.5TEOM}$ calculated from eq 2.

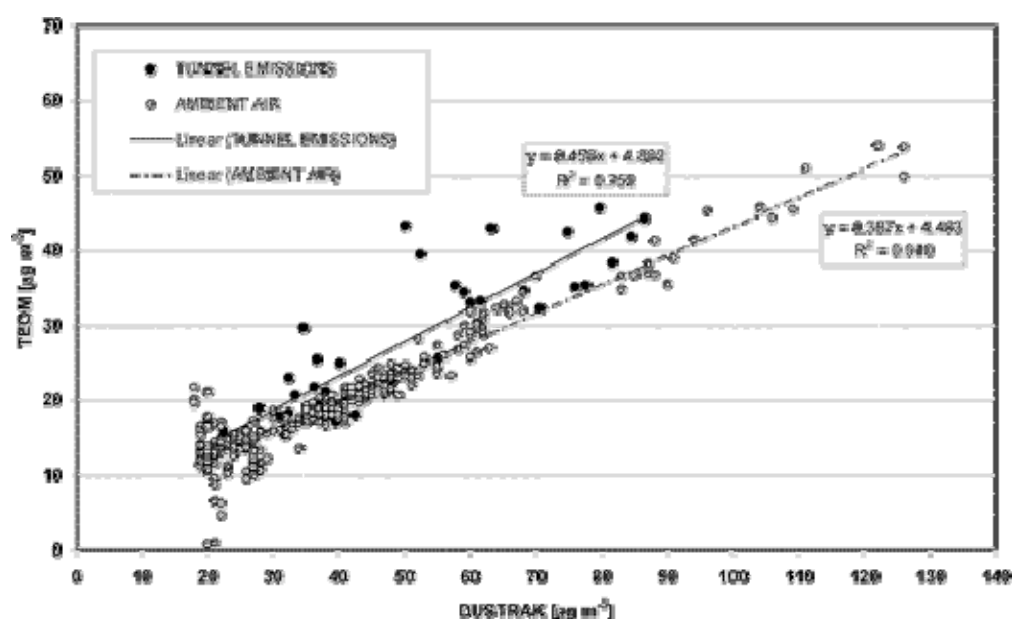**Figure 1** Relationship between $PM_{2.5}$ concentration measured by TEOM and DustTrak for (a) ambient air dominated by traffic emissions including gasoline and diesel engine vehicles and (b) diesel-only emissions measured in the tunnel.

Results and Discussion

Traffic Flow Rate. Time series of traffic flow rate measured during the 2-day monitoring campaign showed similar trends in their temporal variation and comparable values of traffic counts measured at the same time intervals of each day. Figure 2a presents traffic flow rate measured during the second day. On the average

300 bus trips through the tunnel occurred for each measuring day between 16:30 and 22:30, with the traffic count split approximately evenly into half into each direction and each bus making approximately four trips. It can be seen that traffic flow rate reached a maximum at about 18:00 and 21:30, with the second peak somewhat narrower than the first peak.
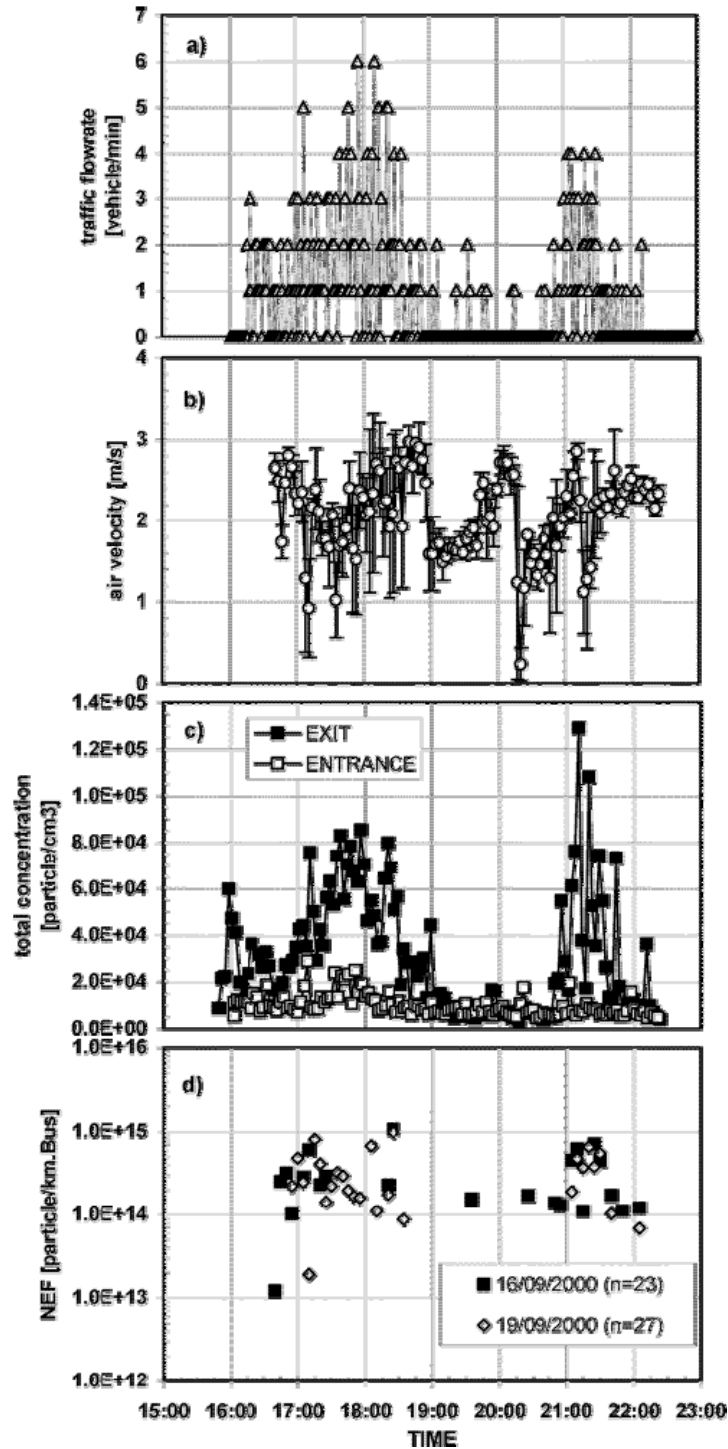

Figure 2 Time series of (a) traffic flow rate, (b) mean air velocity, (c) concentration levels of submicrometer particles measured at the tunnel's entrance and exit, and (d) number emission factors.

Air Velocity in the Tunnel. Air velocity was monitored 50 m away from the tunnel's exit (v_1) and entrance (v_2) with a time resolution of 1 s. The correlation between v_1 and v_2 values over the whole measuring period was better than 80%. Each data set was averaged over 5-min time intervals corresponding to, and aligned with, traffic flow rate and particle characteristics data. The mean values of v_1 and v_2 obtained for each interval were used as input parameters for calculation of emission factors.

Figure 2b presents a time series of the mean air velocities observed during the second measuring day. Similar results were obtained for the first day. The error bars represent standard deviation of v_1 and v_2 values calculated for each time interval. The mean air velocity values fluctuated predominantly within the 1-3 ms^{-1} range with the average of 2.04 ± 0.59 (STD) ms^{-1}. The most dominant factor affecting the air velocity in the tunnel was the number of operating fan units. A sharp decrease in the air velocity values, as observed for example at 17:15 and 20:15 in Figure 1, was caused by a shut down of all fan units by the control system at that time. These data were excluded from the emission factors' calculation. Due to the time and access to the tunnel constraints, the effect of the air velocity cross-gradient was not investigated in this study. The issue is discussed in more detail in Rogak et al. *(10)*.

Particle Number Concentrations. Figure 2c presents time series concentrations of submicrometer particles measured at the tunnel's entrance and exit during the second day. Similar plots were obtained for the first measuring day. The following observations can be made from the presented data:

(i) The concentration levels at the tunnel entrance fluctuated between 0.5 and 1.0 × 10^4 particles cm^{-3}, which could be considered as the urban ambient air background during the course of the measurements. For comparison, 24-h average particle concentration for the year 2000 measured in the Air Monitoring and Research Station distant by about 1 km from the tunnel was 7.3 × 10^3 particles cm^{-3}. An increase in concentrations measured at the entrance between 17:00 and 18:00 could be associated with a higher traffic count at that time period in both directions.

(ii) Concentration levels measured at the tunnel's entrance and exit during none or minimal traffic between 19:00 and 20:30 were low and within a relatively narrow range (0.5-1.0 × 10^4 particles cm^{-3}). This indicates that the effect of local sources on particle concentration measured at both ends was comparable. For no traffic in the tunnel, particle concentration levels in the tunnel were close to those of the surrounding ambient air, with the urban traffic emissions being the main contributing source. The effect of local sources on particle concentration in the tunnel was diminished due to tunnel's geometry, with both ends submerged to an underground level and a minimum distance of 50 m from the nearest road carrying mainly passenger (gasoline) cars.

(iii) Time series of particle concentration levels measured at the tunnel's exit in general followed the trends of the traffic flow rate in the tunnel, with the concentration levels varied between 0.5 × 10^4 up to 8.0 × 10^4 particle cm^{-3}. Studies conducted by Morawska and co-workers *(11, 12)* reported similar concentration values measured at a close vicinity to a busy freeway and also at a monitoring site located near a busy, inner-city road.

The relationship between measured parameters was assessed using nonparametric Spearman rank correlation method. A significant positive correlation was observed

between PM$_{2.5}$ and submicrometer particle concentration levels at the exit ($p = 0.01$) and the traffic flow, indicating that the concentration level of particles in the tunnel was dominated by the emissions of buses travelling through the tunnel. A significant negative correlation at the 0.01 level was observed between PM$_{2.5}$ concentrations measured at the tunnel exit and the average air velocity. Higher air velocity values are related to an increase in outdoor air intake from the entrance portal into the tunnel entry (due to an increase in the number of operating fans, triggered by the SCADA system), which results in an increased dilution of the traffic emissions generated in the tunnel.

Particle Number Size Distributions. Particle size distributions (PSDs) measured at the tunnel's entrance and exit during traffic peak period (17:45-18:15) are presented in Figure 3. The PSD associated with bus emissions are characterized by the presence of two modes: nuclei-mode particles with a peak in the range between 20 and 40 nm and the accumulation mode with a peak at about 100 nm.
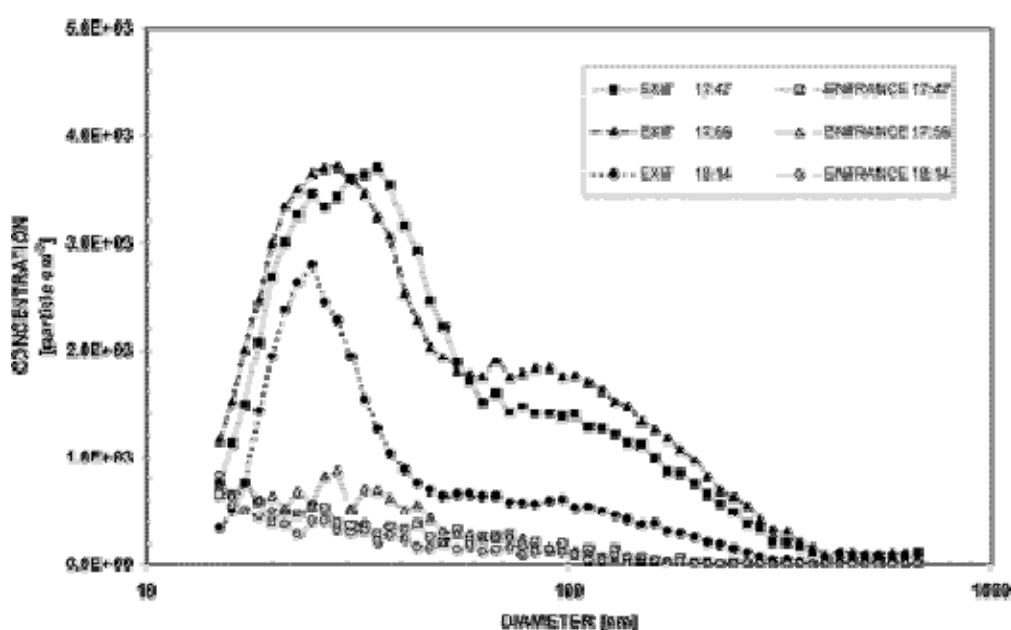

Figure 3 Comparison of particle size distributions of diesel bus emissions for submicrometer particles measured during peak traffic hours at the tunnels' entrance and exit.

The second peak can be attributed to the primary exhaust particles originating from the fuel combustion in the engine, while the first peak, to the secondary, nuclei-mode, particles that are created in a gas-to particle conversion processes (homogeneous nucleation, adsorption and absorption) from the vapor-phase particle precursors as the exhaust dilutes and cools in the atmosphere (13, 14). The size of the secondary particles has been reported in the literature to be in the range from 5 to 50 nm (13, 15, 16).

On the basis of the previous dynamometer studies, PSD of bus emissions is in general unimodal and log-normal, with the location of its peaks varying, and relating to the engine type, model year, vehicle load, and sampling condi tions. In a dynamometer study of 12 diesel buses from Brisbane City bus fleet *(14, 17)*, the authors reported count median diameter (CMD) of particle size distribution for new buses (1999-2001) within the range from 20 to 30 nm, while for the older types of buses the CMD of measured PSD was in the range of 50-70 nm. It appears that the PSDs measured in this study, reflect contribution from both, new and older types of buses to the overall emissions. In addition, the accumulation mode could be also affected by a transforma tion growth of particles from the first mode due to coagulation and condensation processes. Weingartner et al. *(6)* studied the emissions from heavy duty diesel vehicles and reported that the majority of emitted particles were in the size range from 20 to 30 nm. The PSD was bimodal with peaks located at approximately 30 and 100 nm, similar to the results presented here.

Particle Number Emission Factors. The measured data were processed as described above, and the emission factors were calculated according to eq 1. Figure 2d presents the time series of the results obtained for both days. The median value for NEF ($n = 50$) is 2.27×10^{14} particles km^{-1}, with the semi-interquartile range of 1.47×10^{14} particles km^{-1}. The mean value of NEF was 3.11×10^{14} particles km^{-1} with STD 2.41×10^{14} particles km^{-1}. The relatively large variation can be associated with variation in the emission of individual buses in the fleet. As seen from Table 1, the age and mileage of buses included in the tested bus fleet varied significantly. It is also not uncommon to observe significant differences in emissions for buses of similar age and distance travelled. Additional factors that may have contributed to the effect include the variation and error in the tunnel air flow rate, inhomogenity of emissions at the tunnel exit, backflow of outside air through the exit portal into the tunnel, and a relatively poor (5 min) time resolution of SMPS readings.

These results can be compared with measured emission factors of 12 diesel buses, selected from the same Brisbane City bus fleet as tested in this study *(14, 17)*. The measure ments were conducted on a chassis dynamometer for several steady-state modes (constant engine power and speed). For the test conditions equivalent to the study reported in this paper (a bus travelling in the tunnel using 25% of its engine power at a speed 50-70 km h^{-1}), the authors reported a mean NEF value of $(3.87 \pm 2.49) \times 10^{14}$. This is about 25% higher than the value obtained from the tunnel measure ments conducted in this study; however, both results can be considered as in relatively good agreement when taking into account the levels of uncertainties (64% and 77% for dynamometer and tunnel results, respectively). The *t*-test of a difference between both means at 5% significance level was not statistically significant (double-sided *p*-value 0.16).

Table 2 presents a review of particle number and mass emission factors measured in this project and those reported from other studies. There is only limited information available on diesel bus emissions, especially those conducted in a tunnel, or for particle count or PM$_{2.5}$. Therefore, some of the results included in Table 2 were not obtained for the experimental conditions identical to this study or did not measure the same parameters yet were still considered useful for comparison with the current study. A comment, which needs to be made, is that, in general, the results from vehicle emission studies, both laboratory and on-road, are associated with a large variation of measured data. This reflects the naturally occurring variation of measured parameters and not necessarily an error associated with the measuring methodology or

instrumentation used. This is well-documented in Table 2 where the results from several other studies are associated with relatively large variations, or even in some cases no measure of uncertainty is provided. For example, the previous dynamometer studies conducted for Brisbane City buses showed that emission factors of presumably identical buses can vary by a factor of up to 10 *(14, 17)*.

study/ref	method	size fraction measured	method/instrumentation	NEF [a] (particle km^{-1})	MEF [a] (mg km^{-1})
this study	tunnel measurement[c]	0.017-0.7 μm	SMPS (*n* = 50)	$(3.11 \pm 2.41) \times 10^{14}$	610 ± 498
				$(2.27 \pm 1.47) \times 10^{14\,b}$	370 ± 233[b]
		PM2.5	DustTrak (*n* = 94)		583 ± 451
					439 ± 271[b]
			TEOM (estimate from		267 ± 207
			DustTrak, *n* = 94)		201 ± 124[b]
14, 17	chassis	0.008-0.4 μm	SMPS (*n* = 36)	$(3.87 \pm 2.49) \times 10^{14}$	
	dynamometer[d]	TSP	filter/gravimetric method (*n* = 36).		398 ± 218
19	chassis	0.008-0.3 μm	SMPS (*n* = 12)	1.57×10^{14}	137
	dynamometer[e]				
16	engine bench[f]	0.007-0.7 μm	SMPS	$0.5\text{-}1.1 \times 10^{14}$	
15	engine bench test[g]	0.007-0.7 μm	SMPS	1.42×10^{14}	113
21	chassis	PM$_{10}$	DustTrak		679[h]
	dynamometer				377[i]
		TSP	TEOM		911[h]
					494[i]
24	chassis	PM$_{2.5}$			124[j]
	dynamometer[j]				621[k]

Table 2. Number and Mass Emission Factors for Diesel Vehicles Obtained in This Study and Reported from the Literature

18	chassis	>0.010 μm	EAA	3.42×10^{14}	
	dynamometer[l]	PM$_{10}$	IMPROVE sampler		312
27	tunnel experiment	PM$_{2.5}$	IMPROVE sampler		580 ± 260
23	tunnel experiment[m]	PM$_{2.5}$	IMPROVE sampler	na	132 ± 17
		PM$_{10}$			178 ± 13
6	tunnel experiment[n]	PM$_3$	TEOM		384 ± 12
28	tunnel experiment[o]	PM$_{10}$	filter/gravimetric		756 ± 52
		PM$_{1.9}$	filter		429 ± 79

[a] Results are presented as (mean ± STD), unless specified otherwise. [b] Median ± Q (semi-quartile). [c] Bus fleet consisted of approximately 300 diesel-powered BCC buses running at an average speed 60 km/h and engine power of 0.25 P_{max} (estimate). [d] Bus fleet consisted of 12 diesel-powered BCC buses tested at a steady-state mode at speed 40-80 km/h and engine power of 0.25 P_{max}. [e] Bus fleet consisted of 12 diesel-powered buses tested at a steady-state mode at speed 80 km/h and engine power of intermediate (0.5 P_{max}). [f] Two HDV engines tested under steady-state mode at speed 50-70 km/h. [g] Two HDV engines tested under steady-state mode at speed 120 km/h. [h] Two heavy diesel buses (model years 1980-1989) testes at steady-state mode D550 (5% gradient at 50 km/h). [i] Five heavy diesel buses (model years 1996-1999) testes at steady-state mode D550 (5% gradient at 50 km/h). [j] CBD driving cycle with a particulate trap. [k] CBD driving cycle without a particulate trap. [l] Twelve diesel vehicles tested FTP (winter conditions). [m] Fleet of HDV running at steady speed, ~90 km/h. [n] Fleet of HDV running at steady speed, ~100 km/h. [o] 100% HDV (extrapolated from a fleet mix).

Comparison of the results from this study with data from other dynamometer studies conducted under similar test conditions (for example, Cadle et al. reported average NEF of 3.4×10^{14} particle km^{-1} for a set of 12 diesel vehicles tested under Federal Test Procedure measured at winter conditions in United States [18]; Morawska et al. [19] reported the mean value of NEF for particles in the size range 0.008-0.304 μm obtained from a dynamometer study of 12 diesel buses tested under steady-state conditions at 1.6×10^{14} particle km^{-1}) indicates relatively good agreement between these results.

Further analysis of results from Table 2 shows that a bench test of two diesel engines measured at steady-state conditions for 50-70 km/h [16] provided NEF in the range between 0.5×10^{14} and 1.1×10^{14} particles km^{-1}. A previous study by the same research group [15] reported NEF about 1.4×10^{14} particle km^{-1}. These values are lower than our results, indicating that engines' bench test may underestimate the

emissions of on-road operating vehicles. The same conclusion applies for the mass emission factors.

Mass Emission Factors for Submicrometer Particles. Particle mass emissions were estimated from SMPS number concentration measurements assuming particle sphericity and known density. Kittelson *(13)* reported a typical mass-to-volume ratio (effective density) of about 1 g cm^{-3} determined by comparing SMPS volume measurements and filter mass measurements.

The analyses by the scanning electron microscopy indicate that particles present in the diesel emissions, which are mainly carbonaceous soot, are in the form of irregularly shaped clusters or chain-like agglomerates. The monomeres have been identified to be spheres having diameters in the range of 20-30 nm *(20)*. Thus, the sphericity assumption may be relevant for particles in that size range; however, for larger agglomerate particles, the MEF calculated by number to volume conversion may overestimate the real values. This is due to the fact that an equivalent diameter of the agglomerate determined by a measuring instrument (operating on for example a light scattering principle) may be larger than the diameter of a sphere, which has the same volume as the agglomerate. Determination of MEF therefore requires application of more accurate methods, such as gravitational techniques. The presented results of mass emission factors determined from SMPS data (MEF$_{SMPS}$) are thus mainly indicative and need to be viewed in combination with the results obtained by other methods.

The median for MEF$_{SMPS}$ (n = 50) was 370 mg km^{-1} with the semi-interquartile range of 233 mg km^{-1}. The mean value of MEF$_{SMPS}$ was 610 mg km^{-1} with standard deviation of 498 mg km^{-1} (82%). The cause of a relatively large variation is attributed to the same reasons as for the NEF data as discussed previously.

Mass Emission Factor for PM$_{2.5}$. Time series of PM$_{2.5}$ concentration measured by DustTrak at the tunnel's exit during 2 days are presented in Figure 4. Similarly to particle number concentration measured by SMPS, the PM$_{2.5DustTrak}$ concentrations followed the changes in traffic flow rate during monitoring period. Results for each day are similar in terms of the trend as well as the concentration values. PM$_{2.5}$ concentration peaked at 17:30 and about 21:30, with concentration levels exceeding 150 and 100 μg m^{-3}, respectively. The urban PM2.5$_{DustTrak}$ background levels measured during the times with no traffic in the tunnel varied from 10 to 30 μg m^{-3} (PM$_{2.5TEOM}$ equivalent: 8-16 μg m^{-3}) and compared well with the average 24 h PM$_{2.5TEOM}$ concentrations of 8-12 μg m^{-3} measured for the year 2000 at the nearby monitoring station. Elevated levels observed on September 16, 2001 (Saturday) were due to an increase in traffic during the weekend.
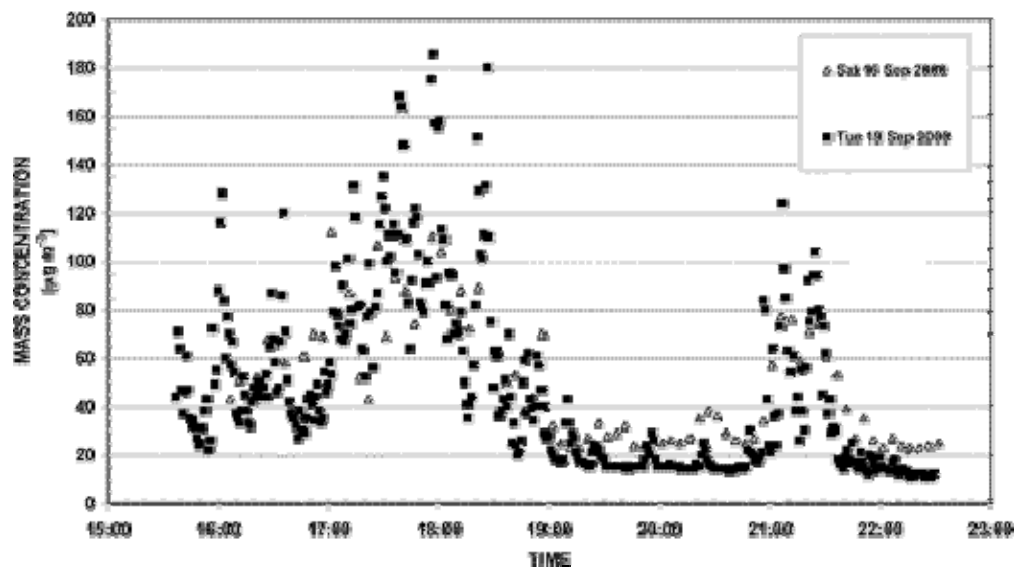
Figure 4 Time series of PM$_{2.5}$ concentration measured by DustTrak at the tunnel's exit.

The PM$_{2.5}$ mass emission factors derived from DustTrak data (MEF$_{DustTrak}$) and TEOM equivalent (MEF$_{TEOM}$) data are presented in Table 2. The mean and median values of MEF$_{DustTrak}$ were 583 ± 451 and 439 ± 271 mg km^{-1}, respectively. Both values are comparable with results obtained from Parsons' study [21], in which the emissions of a small bus fleet (five buses within 1980-1989 and 1996-1999 age groups) were measured by DustTrak under condi tions similar to those in this project. Parsons reported average MEF$_{DustTrak}$ for PM$_{2.5}$ in the range of 377-679 mg km^{-1}.

The mean and median MEF$_{TEOM}$ were 267 ± 207 and 201 ± 124 mg km^{-1}, respectively. It has been shown that TEOM method may underestimate the true mass and consequently the MEF values. This is due to losses of some fraction of semi-volatile material, lost due to evaporation at the instrument's heated inlet. This does not constitute a problem when TEOM is used for measurements of, for example, crustal material with not semi-volatile component, but it is a problem when sampling combustion products that contain a relatively large fraction of such compounds. For example, a study comparing TEOM versus manual gravimetric methods for PM$_{2.5}$ monitoring (a low-volume filter sampler and MOUDI-Micro Orifice Uniform Deposit Impac tor) conducted in four cities in Australia over 15 days revealed systematically lower results from the TEOM, by an average of >30% [3]. Similar results were reported in a study by Moosmuller et al. [9], where TEOM measured PM$_{2.5}$ concentrations were approximately 77% of the PM concentra tions measured by the filter collection method defined in CFR. Thus, the TEOM equivalent could be an underestimation of the true values of the order of 20-30%.

Emission factors of diesel-powered buses measured in this study and those reported from the literature (buses and trucks) of relevance to this study are presented in Table

2. Caution needs to be exercised when comparing the results since differences in testing conditions (tunnel, chassis dynamometer, steady state vs transient driving cycles, type of vehicle etc.), testing methods, and instrumentation applied. In addition to these difficulties, the emission factors are often presented in different units, such as mg km^{-1}; mg kWh^{1}; mg L^{-1} of fuel, which makes a meaningful comparison of the results from different studies (without provisions of all necessary information required for recalculating) very difficult.

In a dynamometer study of 12 buses from the same fleet as in this study, Ristovski et al. *(14)* reported mean value of MEF (n = 36) for total suspended particles (TSP) of 398 ± 218 mg km^{-1}. The authors used the filter gravimetric method. Buses were tested at 25% of maximum power and at velocity of 50-70 km/h. The reported MEF$_{TSP}$ is 1.5 times higher than the mean value of PM$_{2.5}$ MEF$_{TEOM}$ presented in this study (267 mg km^{-1}), which can be related to two factors: (i) TEOM readings are lower as compared to filter-based gravimetric data due to reason discussed above and (ii) the results from this study relate to PM$_{2.5}$ as opposed to TSP. Corrections for the TEOM loses by a factor of 30%; and PM$_{2.5}$/PM$_{10}$ ratio of 0.74 as reported from the emissions studies conducted in Sepulveda tunnel by Gillies et al. *(22)* leads to an estimate of our result at 381 mg km^{-1} (PM$_{2.5}$ MEF$_{TEOM}$ corrected for evaporation loses) and 515 mg km^{-1} (PM$_{10}$ MEF$_{TEOM}$ corrected for evaporation), respectively. The later value is in relatively good agreement with the results from the dynamometer study *(14, 17)*.

The results of MEF for PM$_{2.5}$ from other tunnel experiments vary from 132 ± 17 to 580 ± 260 mg km^{-1} and for PM$_{10}$ from 178 to 416 ± 81 mg km^{-1} *(6, 23)*. Lowenthal et al. *(24)* measured MEF for PM$_{2.5}$ for a set of diesel trucks and buses without particulate trap for a CBD driving mode simulated on a chassis dynamometer and reported value of 621 mg km^{-1}. The higher value than measured in this study may be attributed to different driving cycle and the inclusion of diesel trucks in the tested sample. Heavy diesel trucks are recognized as stronger emitters of PM compared to buses. Keeping in mind the difficulties when comparing data from different studies, the results from this study are in general comparable with those reported from the literature.

It is interesting to compare the results from this study with the data used for an assessment of the emissions inventories since they are used to estimate the overall impact of the traffic emissions on human health and environment. Only limited information is available in relation to diesel bus emissions. The UK database for PM$_{10}$ MEF for buses in urban driving *(25)* presents values of 830 (1997); 747 (1998); 674 (1999); 517 (2000); 384 (2001); and 349 (2002) mg km^{-1}. The number in parentheses indicates the model year of a bus. The estimate of mean value of MEF$_{TEOM}$ for PM$_{10}$ derived in this study (MEF$_{TEOM}$ ~515 mg km^{-1} including the corrections for evaporation losses and PM$_{2.5}$/PM$_{10}$ ratio) is close to UK values relevant for the year 2000. Similarly, PM$_{10}$ MEF calculated from a particle matter emission factor model (PMFAC) for diesel-powered buses at 50-70 km h^{-1} velocity is in the range from 1.1 to 1.2 g km^{-1} *(26)*. These values are commonly used for emission inventory development in Europe, which may lead to an overestimation of the PM load originating from bus emissions.

In summary, this study not only provided the emission factors for an important part of urban traffic, diesel-powered buses, but also demonstrated that when carefully designed both approaches, dynamometer and on-road studies, provide comparable

results applicable for the assessment of the effect of traffic emissions on airborne particles pollution.

Acknowledgment

Supporting Information Available

Data set for determining NEF for submicrometer particles and descriptive statistics NEF. This material is available free of charge via the Internet at http://pubs.acs.org.

* Corresponding author phone: +61 7 3864 1133; fax: +61 7 3864 9079; e-mail: m.jamriska@qut.edu.au.

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