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Diesel Bus Emissions of Submicrometer Particles Measured in a Tunnel Study

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Summary

The emission factors of a bus fleet consisting of approximately three hundreds diesel powered buses were measured in a tunnel study under well controlled conditions during a two-day monitoring campaign in Brisbane. The number concentration of particles in the size range 0.017-0.7 μm was monitored simultaneously by two Scanning Mobility Particle Sizers located at the tunnel's entrance and exit. The mean value of the number emission factors was found to be $(2.44 \pm 1.41) \times 10^{14}$ particles 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, thus indicating 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.

Keywords: *emission factor; submicrometer particles; bus fleet; tunnel study*.

1. Introduction

Knowledge of vehicle emission factors is essential for developing emission inventories, for modelling 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].

The most commonly used methods for determination of the emission factors are dynamometer studies (a vehicle driven through a certain driving cycle) and on-road studies. Controllability of the testing conditions and the resulting comparability of the values derived are the main advantages of the first method, however, its serious limitations are the costs and the complexity. These limitations mean that often only a small number of vehicles is tested, unrepresentative of the overall composition of the vehicle fleet on the roads. Additionally, dynamometer conditions are not necessarily representative of real road conditions.

The advantage of on-road measuring 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 as well as vehicle fleet mix on the road. It is thus usually very difficult to estimate the emission factors of individual classes of vehicles (for example petrol driven versus diesel or diesel buses versus trucks). This method is not included in any standard testing procedures.

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: a) increasing the number of on-road studies, and conducting them for conditions as best controlled and defined as possible; and b) 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 constituted the purpose of the work reported here, the aims of which were:

- To determine the bus emission factors through a well controlled road study.
- To compare the emission factors obtained from the road measurements in the first instance with the dynamometer studies conducted in Brisbane, and secondly with the emission factors reported in the literature.

A particularly good opportunity arrived with the opening of a tunnel in the inner city of Brisbane for use by 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 two hours later, to take them back to the centre 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.

2. Experimental

The measurements were conducted over two 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 two hours. The measurements commenced every day before the bus traffic started building up and continued for some period after it completely ceased.

2.1. Tunnel description

The study was conducted in Woolloongabba bus-way tunnel 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. 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, NO_x and air visibility as the input parameters. These are measured by ten 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.

2.2. Instrumentation

Particle size distribution (PSD) and concentration levels were measured by two Scanning Mobility Particles Sizers (SMPS) operating in the size range 0.017-0.7 μm and time resolution of 3 minutes. 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).

2.3. Study design

Particle characteristics were 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 internal diameter 0.01m. 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 (Willeke and Baron 1993) and found to be negligible.

Traffic was monitored by visual recording of the number of buses travelling in and out of the tunnel in one-minute intervals. The traffic flowrate at its peak was approximately 5 buses min^{-1}. Almost all of the vehicles were diesel engine powered buses with the year-model ranging from 1990 to 2001, and mileage of up to 10^6 km.

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 1m 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 over three-minute time intervals was used for the emission factors calculation.

2.4. Determination of emission factors

Particle number emission factor (NEF) was calculated from the formula (Weingartner *et al*. 1997, Grosjean *et al*. 2001):

$$EF = \frac{(C_{Exit} - C_{Entrance}).v_{air}.S}{L.N}. \qquad [1]$$

where C_{Exit}, $C_{Entrance}$ are particle number or mass concentration measured at the tunnel's exit and entrance, respectively; ν_{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.

3. Results and discussion

3.1. Traffic flow rate

Time series of traffic flowrate measured during the two-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 1a presents traffic flowrate 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 flowrate reached a maximum at about 18:00 and 21:30, with the second peak somewhat narrower than the first peak.

3.2. Air velocity in the tunnel

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

Figure 1b 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, v_2 values calculated for each time interval. The mean air velocity values fluctuated predominantly within the 1 to 3 m/s range with the average of 2.04±0.59 (STD) m/s. 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, was caused by a shut down of all fan units by the control system at that time. This data was excluded from the emission factors' calculation. Due to the time and access to the tunnel constrains 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.* (1998).

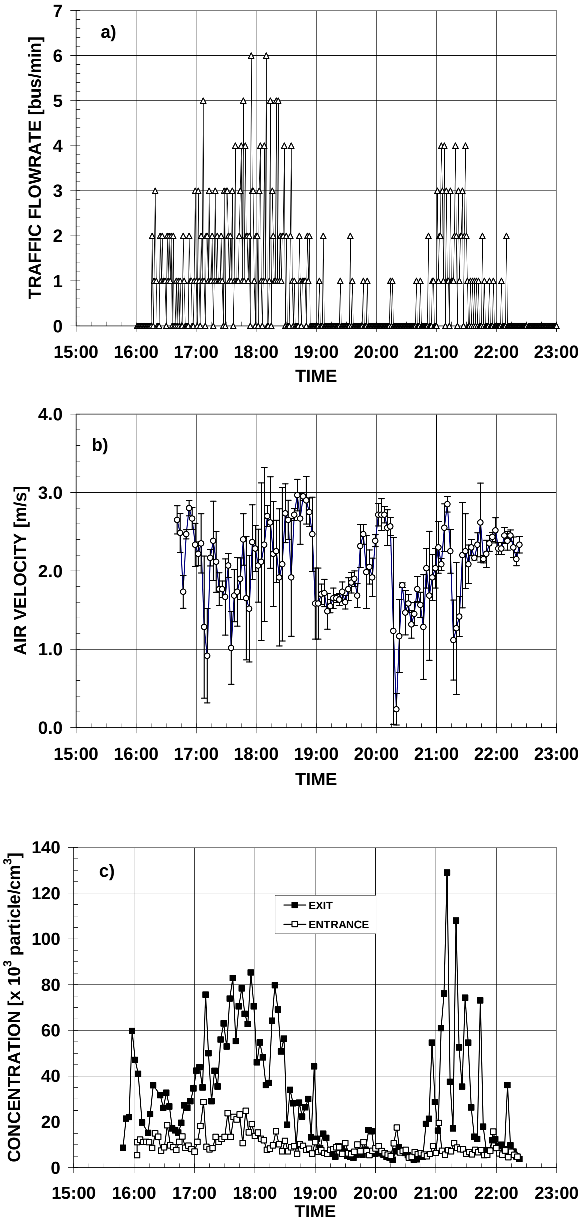

Figure 1 Time series of a) traffic flowrate; b) mean air velocity; and c) concentration levels of submicrometer particles measured at the tunnel's entrance and exit**.**

3.3. Particle number concentrations

Figure 1c 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-hour 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) During none or minimal traffic between 19:00 and 20:30 the concentration levels measured at the tunnel's entrance and exit 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 were 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 flowrate in the tunnel, with the concentration levels varied between 0.5×10^4 up to 8.0×10^4 particle cm^{-3}. Studies by Morawska *et al*. (2002a) and Jamriska *et al*. (1999) 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.

3.4. 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 2. The PSD associated with bus emissions are characterised by the presence of two modes: nuclei-mode particles with a peak in the range between 20 to 40 nm; and the accumulation mode with a peak at about 100 nm.

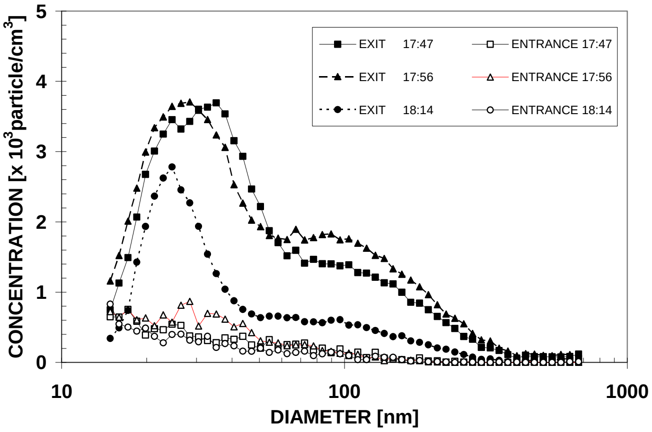

Figure 2 Comparison of particle size distributions of diesel bus emissions for submicrometer particles measured during peak traffic hours at the tunnels' entrance and exit

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 vapour phase particle precursors as the exhaust dilutes and cools in the atmosphere (Kittelson 2001). The size of the secondary particles has been reported in the literature to be in the range from 5 to 50 nm (Ristovski *et al*. 2002, CONCAWE 2001, Morawska *et al*. 2002b)

Based on the previous dynamometer studies, PSD of bus emissions is in general unimodal and lognormal, with the location of its peaks varying, and relating to the engine type, year-model, vehicle load and sampling conditions. In a dynamometer study of 12 diesel buses from Brisbane city bus fleet (Ristovski *et al*. 2002) 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 transformation growth of particles from the first mode due to coagulation and condensation processes. Weingartner *et al*. (1997) 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 nm and 100 nm, similar to the results presented here.

3.5. Particle number emission factors

The measured data was processed as described above and the emission factors calculated according to Eq.1. The median value for NEF (n=48) is 2.44×10^{14} particles km^{-1}, with the semi-interquartile range of 1.41×10^{14} particles km^{-1}. The mean value of NEF was 3.18×10^{14} particles km^{-1} with SD 2.16×10^{14} particles km^{-1}. The relatively large variation was caused by several factors including: variation in the emission of individual buses in the fleet; variation in air flowrate and a relatively large (3 minutes) 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 (Ristovski *et al*. 2002, Morawska *et al*. 1998). The measurements 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 to 70 km h^{-1}), the authors reported a mean NEF value of $(3.87\pm2.49)\times10^{14}$. This is about 20% higher than the value obtained from the tunnel measurements 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 47% for dynamometer and tunnel results, respectively).

Table 1 presents a review of particle number 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. Therefore, some of the results included in Table 1 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 1 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 (Ristovski *et al*. 2002, Morawska *et al*. 1998).

Comparison of the results from this study with data from other dynamometer studies conducted under similar test conditions (for example Cadle et al. (1999) 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 USA (Code of Federal Regulations). Morawska *et al*. (1998) 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.

Table1 Number and mass emission factors for diesel vehicles obtained in this study and reported from the literature

Study/Reference	**Method**	**Size Fraction (μm)**	**Instrumentation**	**NEF $^{a)}$ (particle km^{-1})**
This Study	Tunnel measurement $^{c)}$	0.017-0.7	SMPS (n=48)	$(3.23\pm2.16)\mathrm{x}10^{14}$ $(2.44\pm1.41)\mathrm{x}10^{14}$ $^{b)}$
Morawska et al. 2002	Chassis Dynamometer $^{d)}$	0.008-0.4	SMPS (n=36)	$(3.87\pm2.49)\mathrm{x}10^{14}$
Morawska et al. 1998	Chassis Dynamometer $^{e)}$	0.008-0.3	SMPS (n=12)	$1.57\mathrm{x}10^{14}$
CONCAWE 2001	Engine bench $^{f)}$	0.007-0.7	SMPS	$0.5\text{-}1.1\ \mathrm{x}10^{14}$
CONCAWE 1998	Engine bench test $^{g)}$	0.007-0.7	SMPS	$1.42\mathrm{x}10^{14}$
Cadle et al. 1999	Chassis Dynamometer $^{h)}$	>0.010	EAA	$3.42\mathrm{x}10^{14}$

$^{a)}$ Results are presented as (mean ± SD), 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: 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: 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: intermediate (0.5 P_{Max}); $^{f)}$ 2 HDV engines tested under steady-state mode at speed 50-70 km/h; $^{g)}$ 2 HDV engines tested under steady-state mode at speed 120 km/h; $^{h)}$ 12 diesel vehicles tested FTP (winter conditions).

Further analysis of results from Table 1 shows that a bench test of two diesel engines measured at steady state conditions for 50-70 km/h (CONCAWE 2001) 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 (CONCAWE 1998) 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.

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.

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