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Relation between Indoor and Outdoor Exposure to Fine Particles near a Busy Arterial Road

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Abstract Various studies on indoor and outdoor particulate matter in the urban environment in the vicinity of busy arterial roads in the centre of the subtropical city of Brisbane have indicated that the revised United States Environmental Protection Agency National Ambient Air Quality Standards (US EPA NAAQS) for Particulate matter $PM_{2.5}$ could be exceeded not only outdoors but also indoors. The aim of this work was to investigate outdoor exposure to submicrometer particles and their relationship with indoor exposure in a hypothetical office building located in the vicinity of a busy arterial road. The outdoor exposure values and trends were measured in terms of particle number in the submicrometer size range and were then recalculated to represent mass concentration trends. The results of this study indicate that exposure to $PM_{0.7}$ particles in ambient air close to a busy road often exceeds the levels of the annual and 24-hour US EPA NAAQS $PM_{2.5}$ standards. It is likely that exposure to $PM_{2.5}$ is even higher, and may significantly exceed these standards.

Key words Indoor air; Outdoor air; Exposure; Particles; $PM_{2.5}$; US EPA NAAQS.

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Introduction

In recent years, exposure to fine airborne particles has been identified as an important factor affecting human health, and linked to a range of different health end points. Numerous studies have shown a clear correlation between health problems, including respiratory and cardiovascular diseases, as well as increased hospitalisation rate and increased mortality, and exposure to fine airborne particles (Dockery et al., 1993; Schwartz and Markus, 1990; Pope et al., 1992; Department of Health Committee on Medical Effects of Air Pollutants, 1995). Depending on size, respirable particles penetrate to and are deposited in various regions of the respiratory tract. Smaller particles can penetrate deeper into the tract and can deposit there with a higher probability than larger particles due to their larger diffusion coefficient. Submicrometer particles (smaller than one micrometer) represent the majority of particles by number in ambient air. In an urban environment where motor vehicle emissions constitute the main source of fine particles (Morawska et al., 1998a) more than 80% of particles in outdoor air are smaller than 0.1 micrometer (ultrafine particles) (Morawska et al., 1996a). While there is still the need to establish better epidemiological links between exposure and health effects, as well as to identify the mechanisms which underlie the effects, it has been recognised that action should be taken to lower exposure. This was expressed through the United States Environmental Protection Agency's revised National Ambient Air Quality Standards (US EPA NAAQS, 1997) which extended the classification of acceptable concentration levels of particulate matter in ambient air to include a new category of $PM_{2.5}$ (particulate smaller than 2.5 micrometer). At present there are no standards or guidelines for particle concentration in indoor, non-industrial environments.

Outdoor air quality significantly affects indoor air quality and in the absence of major indoor sources, intake of outdoor air constitutes the main source of pollutants in the indoor environment (Dockery and Spengler, 1981; Wallace, 1996). For example, studies conducted in office buildings (Jamriska et al., 1998a), and in hospitals (Morawska et al., 1996b) located near busy arterial roads in the centre of Brisbane, Australia, showed that outdoor particles (both fine and larger) were the most important source of indoor particles. In terms of regulations, including standards and guidelines for acceptable concentration levels, indoor and

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outdoor air are treated separately, as they are usually the responsibility of different government bodies. However, in terms of human exposure assessment, indoor and outdoor air cannot be separated and both should be considered as interacting environments, for which combined exposure is calculated.

Various studies on indoor and outdoor particulate matter in urban environments in the vicinity of busy arterial roads in the centre of the subtropical city of Brisbane (Morawska et al., 1998a; Jamriska and Morawska, 1996) provided indications that the revised US EPA NAAQS standards for $PM_{2.5}$ could be exceeded not only outdoors but also indoors. The road system in Brisbane is spread throughout relatively densely populated urban areas, which may increase the exposure of a large fraction of the community who work or live in nearby areas. Indoor exposure due to outdoor sources could be decreased if efficient ventilation systems were in place, but most residential houses in South-East Queensland, including those close to busy roads, are only ventilated naturally. Office buildings on the other hand, where mechanical ventilation and air filtration are a standard practice, do not use filters, that would perform efficiently for fine particles. In general, the reduction efficiency of the air-handling systems installed in these buildings has not been assessed for $PM_{2.5}$ or for the submicrometer particles in relation to the local outdoor conditions.

The work presented here was aimed at investigating in the first instance, outdoor exposure to submicrometer particles and its relationship with indoor exposure in an office building located in the vicinity of a busy arterial road. Exposure was measured in terms of particle number. Using a simple mathematical model, the evolution of the number concentration of submicrometer particles in indoor air was calculated and the effects of ventilation and filtration on particulate reduction were assessed. As a second step, exposure expressed in terms of particle number concentrations as a function of time, was recalculated to represent mass concentration trends, and was then correlated to $PM_{2.5}$ exposure and compared with the US EPA $PM_{2.5}$ standards. The correlation was done by experimental identification of correlation factors between particle number and gravimetric mass measurements for the study area.

While the study does not provide a comprehensive evaluation of the exposure to airborne fine particles for all traffic scenarios nor for other urban design conditions, the results presented here may be used as a useful indication of the level of outdoor exposure and their relation to indoor exposure. Knowledge of these is critical in planning urban development as well as for control of exposure of outdoor origin in existing buildings.

Experimental Methods

The project involved the measurement of number size distribution and concentration of submicrometer particles, as well as the mass concentration of $PM_{2.5}$ particles in an outdoor location near a busy road. The other parameters monitored were wind direction and velocity, air temperature and relative humidity (Morawska et al., 1998b). Using the data obtained from outdoor monitoring, indoor particle concentrations and their variation were calculated for a building, which would be located in an environment of characteristics similar to the outdoor sampling site. This was done using a simple particle number balance model and applying as input parameters, building operational conditions typical for Brisbane.

Instrumentation

Scanning Mobility Particle Sizer (SMPS)

The SMPS consists of the 3071A TSI Electrostatic Classifier and the 3010 Condensation Particle Sizer. The instrument operates in the size range 0.01 to 1 μm. Before sampled air enters the classifier, larger particles are removed by an inertial impactor. In the electrostatic classifier the sample passes through a charger, which imparts a bipolar equilibrium charge level to the particles. The charged aerosols are introduced into a laminar flow of sheath air and travel between two axial cylinders of the differential mobility analyser, where they are classified according to their electrical mobility. Depending on the high voltage applied between the cylinders, a fraction of particles of the same mobility is selected and then counted by the particle condensation counter. Throughout the sampling process the voltage on the electrostatic classifier ramps, which corresponds to a continuous scan of mobility and therefore of particle size. The measurement process is controlled by an interfacing computer.

Tapered Element Oscillating Microbalance (TEOM)

The TEOM is an instrument which measures particle gravimetric mass in real time based on the theory of a damped oscillating spring (Willeke and Baron 1993). Sampled air passes at a constant flow rate through a filter attached to a tapered oscillating glass rod. The change in filter mass caused by accumulated particles results in a change of the oscillation frequency. Monitoring the frequency leads to the determination of particle mass concentration. The TEOM is certified by the US EPA as an equivalent to gravimetric techniques for

PM_{10} and $PM_{2.5}$ measurements in ambient air. Using inlet heads of different cut-off points, the instrument measures mass concentration for particles of these size ranges. In the presented study, an inlet head for $PM_{2.5}$ measurements was used.

Methodology

Monitoring of outdoor ambient particles

Outdoor monitoring was conducted at a site located at a distance of approximately 10 m from a busy arterial road, the South East Freeway, in the centre of Brisbane, with traffic flowing in three lanes in each direction. At the sampling point, the road is elevated 3 metres above the ground level leading to a bridge across the Brisbane River. No other significant particle sources were present near the sampling point.

Number and size distributions of submicrometer particles were measured by the SMPS in the size range 0.016 to 0.700 micrometers. The measurements were conducted over a period of three weeks in the November/December period (run 1), with triplicate samples collected every 15 min between 6:00 a.m. and 6:00 p.m. for each day. The duration of each measurement was two minutes. The wind parameters, air temperature and relative humidity were continuously monitored at the Air Monitoring and Research Station (AMRS) located 210 m from the sampling point and considered as not to be directly influenced by the freeway traffic (Morawska et al., 1998a).

Correlation of particle number and mass

Correlation between $PM_{0.7}$ and $PM_{2.5}$ was established in experiments where SMPS and TEOM were set up for simultaneous monitoring of ambient air (runs 2 and 3). The mass concentration of $PM_{2.5}$ was measured by the TEOM. Mass concentration of $PM_{0.7}$ particles was calculated from the SMPS number concentration measurements by assuming particle sphericity (Nazaroff and Cass, 1989) and a conservative estimate, for particle density of 1.0 $g \cdot cm^{-3}$ (Morawska et al., 1998a). These measurements, conducted in February, after completion of run 1, were performed close to the freeway (one-day monitoring – run 2) and at AMRS (two-week monitoring – run 3).

Prediction of particle mass concentration indoors (mathematical modelling)

The evolution of particles indoors could be predicted by using mathematical models. Most of the models are based on the particle mass balance and vary from very simplistic forms, such as in (Shair and Heitner 1974; Alzona et al., 1979; Dockery and Spengler, 1981; Ekberg, 1994, 1996; Tichenor et al., 1990, 1993; Koutrakis and Briggs, 1992; Ozkanayk et al., 1996; Salvigni et al., 1996) and others, where only the total concentration of suspended particulate matter is predicted, to the more complex models (Gelbard and Seinfeld, 1980; Warren and Seifeld, 1985; Nazaroff and Cass, 1989; Seigneur et al., 1986; Whitby and McMurry, 1997), which incorporate particle size, chemical composition and aerosol dynamics. In this paper, the mass concentration of airborne particulate indoors was predicted using a simple mathematical model (Jamriska et al., 1998a) based on the particle number balance equation (Appendix). It assumes a uniform distribution of particles within the indoor space. The time derivative of the total particle number equals the sum of particles introduced from outside and that generated by indoor sources, minus particle losses due to their deposition and air exfiltration. In general, the model could be used for both naturally and mechanically ventilated indoor environments. This is achieved through a selection of corresponding input parameters. In this study the model was applied to an office environment in a mechanically ventilated building.

The input parameters required are the initial indoor particle concentration, evolution of outdoor air concentration and Heating, Ventilation and Air Conditioning (HVAC) operational parameters. The latter is represented by the airflow of outside (O/A), return (R/A) and supply (S/A) air, the air exchange rate, and the reduction of particles in the HVAC system caused by filtration and particle deposition on the cooling coil ($\varepsilon_{S/A}$). The effect of particle losses due to deposition in duct systems and on indoor surfaces was assumed to be negligible, as the rate of removal by deposition is much smaller than that typically due to HVAC system (Nazaroff and Cass, 1989). Changes in particle characteristics due to particle dynamics, i.e., coagulation, condensation, evaporation and other processes (Hinds, 1982) were considered insignificant, as these are minor effects under the concentrations and indoor conditions encountered in this study (Thatcher and Layton, 1995). For example, the coagulation effect would reduce the initial indoor concentration of 7.5×10^3 particles $\cdot cm^{-3}$ (ultrafine particles) over the period of 1 h, by less than 3% (Hinds, 1982).

The interaction of particles with heating/cooling coil inside of the HVAC system, as the air passes through the unit, are of a short duration and observed changes in the particle size due to the condensation are not significant (Jamriska and Morawska, 1996). Reduction in particle concentration is incorporated into the overall filtration efficiency of the HVAC system ($\varepsilon_{S/A}$), including both, filtration by filters and the effect of cooling/heating coil.

The evolution of particle concentration indoors is calculated in time steps, with the predicted indoor concentration at the end of i^{th} interval $C(t_i)$, being the initial indoor concentration $C_o(t_{i+1})$ at the beginning of the next, $(i+1)^{th}$, interval. The corresponding outdoor concentration $C_{O/A}(t_{i+1})$, either measured or estimated, needs to be provided for each time interval. The initial indoor concentration $C_o(t_1)$ for the first interval was estimated by the corresponding outdoor air concentration. The model could predict both number and mass concentration of particles. The number and length of steps selected are arbitrary, however, they need to be small enough to include rapid changes, for instance peak hour traffic and changes in HVAC operation. In this study 24 steps were used, each of 30 min duration. The HVAC operational parameters could be set as constant or could vary throughout the modelling period.

The model has been extensively validated with experimental data and showed very good correlation between predicted and measured particle characteristics (Jamriska et al., 1998a, 1998b).

Results and Discussion

Monitoring of Outdoor Ambient Particles

Figure 1 presents the number and mass concentrations of particles monitored in the first run over three weeks. The wind conditions varied during the day, with south-easterly winds (from the freeway) prevailing in the morning and northerly (towards the freeway) winds in the afternoon (Morawska et al., 1998b). Although the concentrations appear well spread in the time profile, a pattern is evident where an increase in concentration occurs coinciding with peak hour traffic conditions between 8:00 and 9:00 a.m. and decreasing throughout the rest of the day.

The averaged particle number concentrations estimated from the best fit line (polynomial regression, R^2=0.60) were in the range from 7.5×10^3 to 3.7×10^4 particles · cm^{-3} for both morning and afternoon measurements, while the individual concentrations reached a level of almost 6.1×10^4 particles · cm^{-3}. The average concentration for the 6.00 a.m. to 6.00 p.m. period was 2.1×10^4 particles · cm^{-3}. The 24-h averaged concentration was 1.4×10^4 particles · cm^{-3}. The averaged concentration levels outside of the best fit line (6:30 p.m.–5:30 a.m.) for both number and mass particle concentration were estimated by the average concentrations measured at the AMRS over the period of 3 years (Morawska et al., 1998a).

The range of averaged $PM_{0.7}$ mass concentrations (best fit line–polynomial regression, R^2=0.54) were between 26 μg · m^{-3} and 160 μg · m^{-3}. The 24-h average $PM_{0.7}$ mass concentration was 52 μg · m^{-3}, and the average concentration for the 6.00 a.m. to 6.00 p.m. period was 78 μg · m^{-3}. The mass concentration was calculated from the measured number size distribution

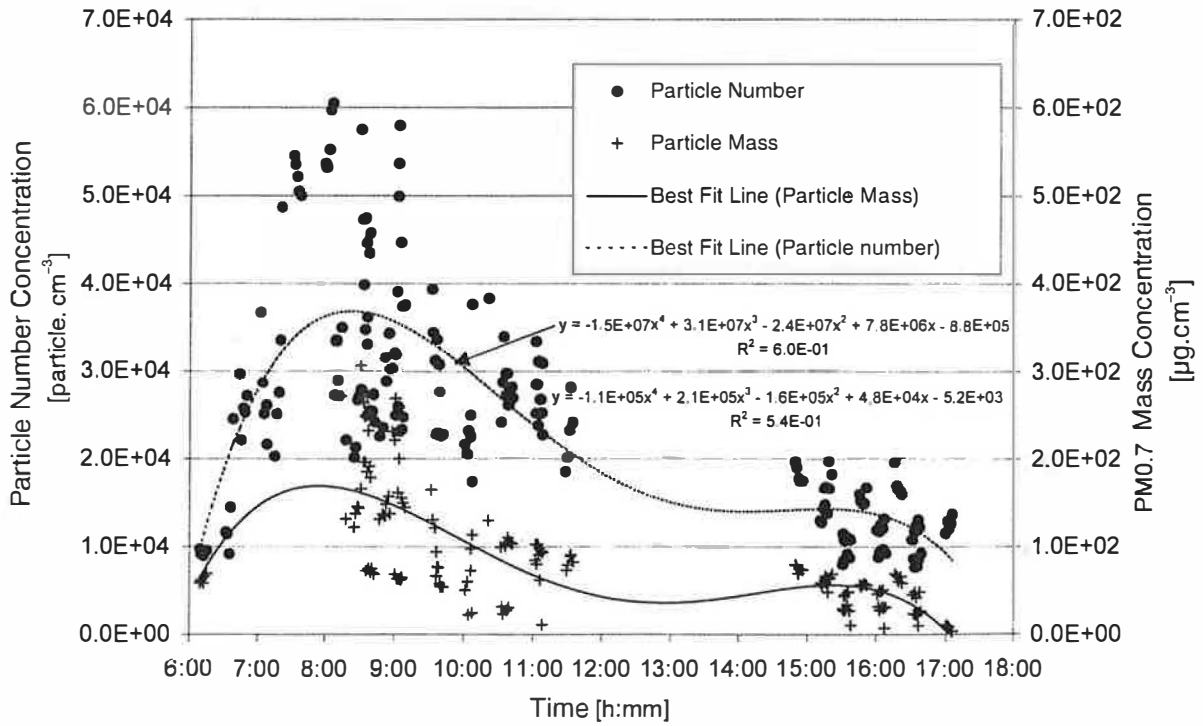

Fig. 1 Total particle number and mass concentration measured at the freeway (run 1)

using a conservative estimate of an average ambient aerosol particle density at 1.0 $g \cdot cm^{-3}$. Recent studies based on simultaneous monitoring of volume and mass concentrations for $PM_{1.0}$ showed that the particle density vary during a day and reported an average particle density of $1.7 \times 1.0\ g \cdot cm^{-3}$ (Morawska et al., 1998a).

The 24-h average concentration of $PM_{0.7}$ identified in this work exceed the annual, and is close to the 24-h US EPA $PM_{2.5}$ standards. Areas are in compliance with the new US EPA annual standard when the 3-year average of the annual arithmetic mean of $PM_{2.5}$ concentrations is less than or equal to 15 $\mu g \cdot m^{-3}$. The new 24-h $PM_{2.5}$ standard of 65 $\mu g \cdot m^{-3}$ is based on the

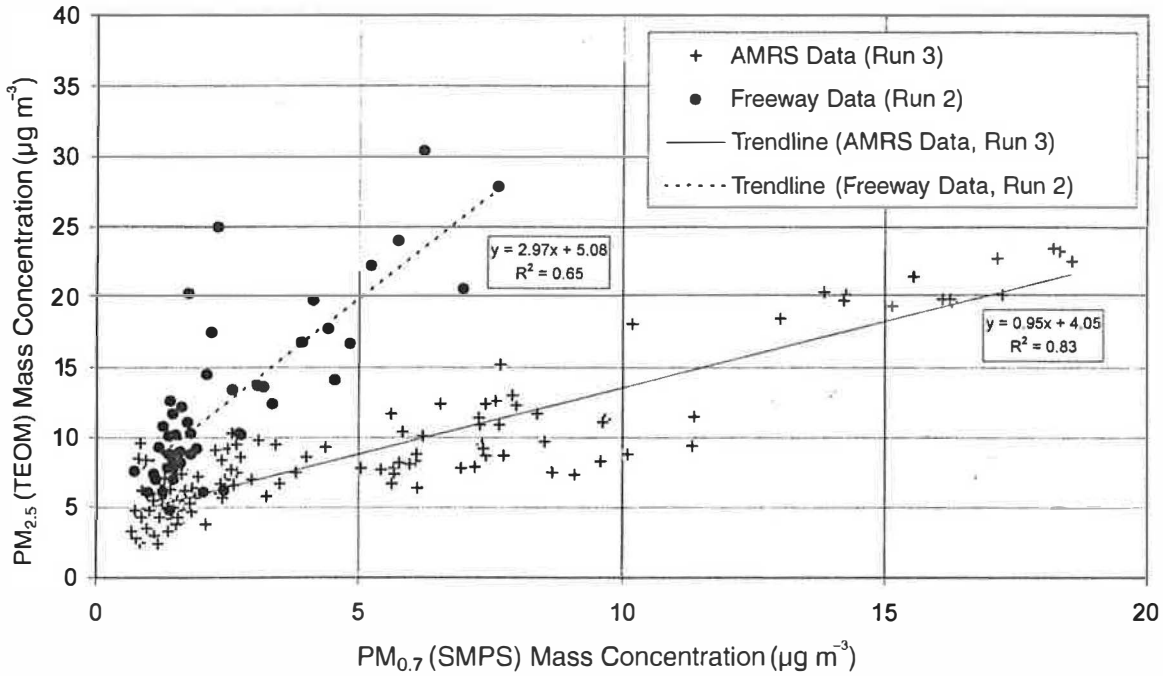

Fig. 2 Relation between measured $PM_{2.5}$ and calculated $PM_{0.7}$ mass concentration

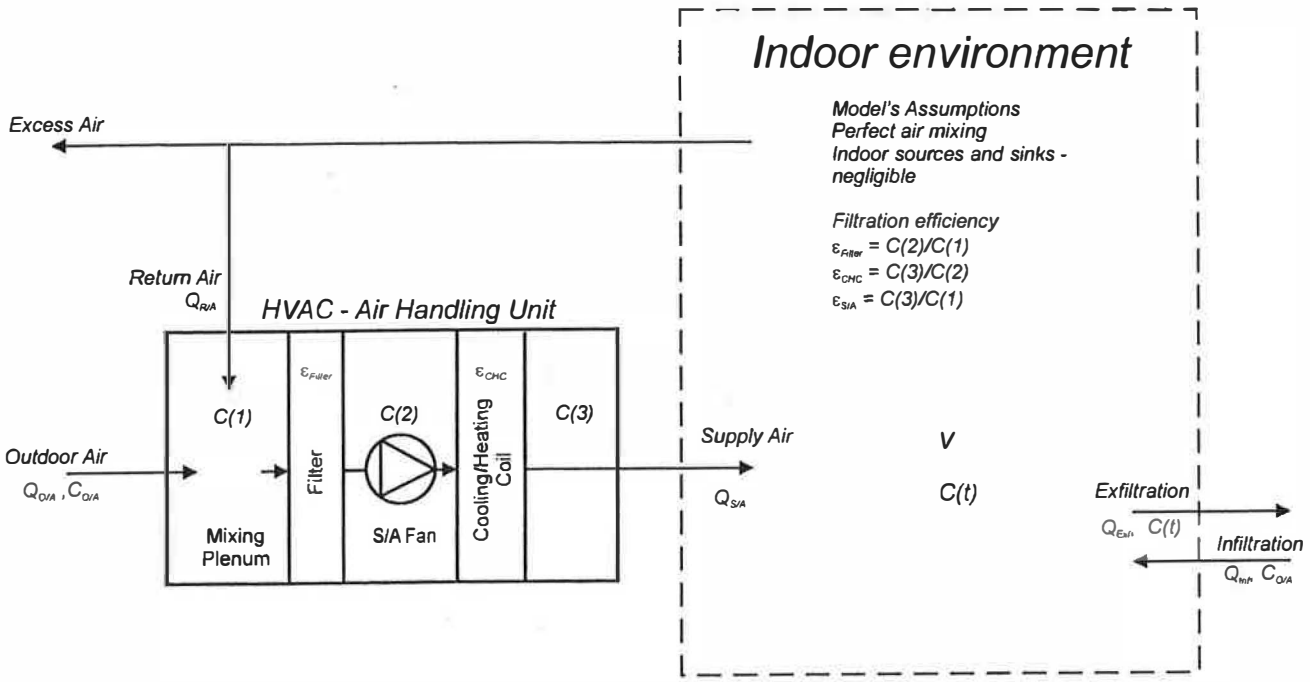

Fig. 3 Schematic diagram of the indoor space, HVAC system and model input parameters

99th percentile of 24-h concentrations in a year (averaged over 3 years).

Correlation between $PM_{0.7}$ and $PM_{2.5}$ in Ambient Outdoor Air

Figure 2 presents relations between measured $PM_{2.5}$ (TEOM data) and calculated $PM_{0.7}$ (from SMPS particle number characteristics) mass concentrations for the two investigated locations (near the road and in the AMRS). As can be seen, the results differ depending on the sampling location. The trend in variation of the $PM_{2.5}$ measured next to the freeway during the day was similar to the trend exhibited for particle number concentration (Figure 1), with maximum values measured from 6:00 a.m. to 10:00 a.m.

A linear relationship between $PM_{2.5}$ and $PM_{0.7}$ mass

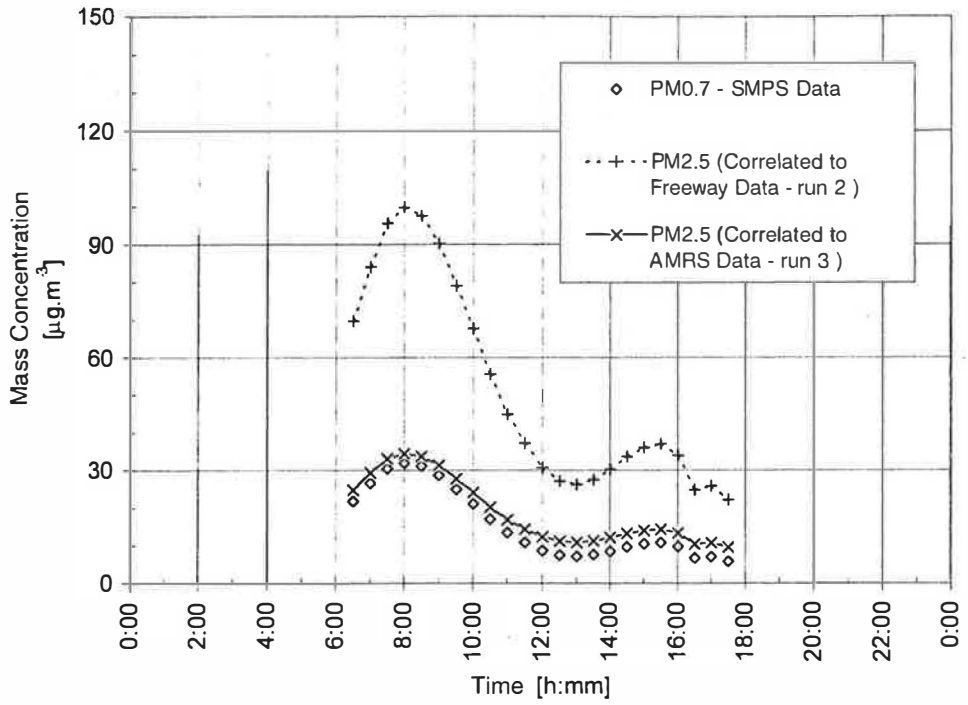

Fig. 4 Predicted $PM_{0.7}$ and $PM_{2.5}$ mass concentration indoors ($\varepsilon_{S/A}$= 34%)

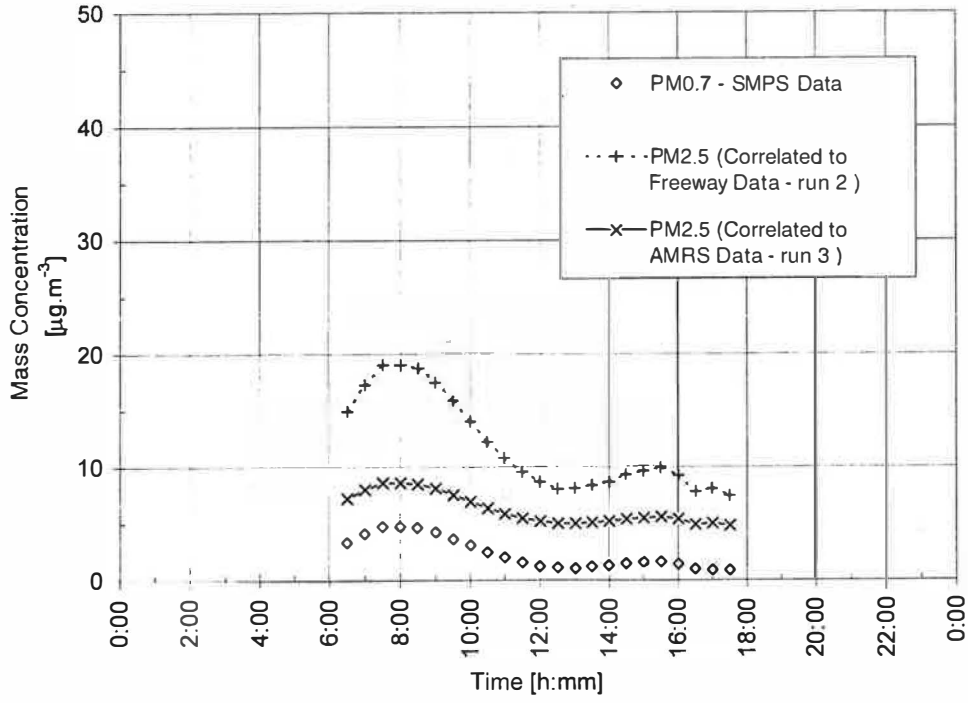

Fig. 5 Predicted $PM_{0.7}$ and $PM_{2.5}$ mass concentration indoors ($\varepsilon_{S/A}$= 85%)

concentrations was identified for both investigated conditions with correlation factors (slopes of the trend lines in Figure 2) of 1 and 3 for the AMRS (run 3) and freeway measurements (run 2), respectively. It can be concluded that the mass concentration of $PM_{2.5}$ predicted from particle number measurements ($PM_{0.7}$) could be up to three times the value of the mass concentration calculated for $PM_{0.7}$, assuming a particle density of 1 $g \cdot cm^{-3}$.

The slopes of the trend lines could also be interpreted as arbitrary values for the ambient aerosol density (the mass of fine particles was calculated as the product of volume concentration and a unit particle density). The term arbitrary is applied as the TEOM and SMPS operated in different size ranges.

The variation in the correlation factors may be associated with differences in aerosol conditions between the two locations. Near the road, fresh motor vehicle emissions are characterised by smaller sizes of particles in the submicrometer range than the aged particles further away from the road. The particle aging process (usually growth in size) results from condensation or coagulation processes. At the same time, however, concentration of larger particles near the road, constituting dust from the road resuspended by the vehicles, is higher than further away from the road.

Prediction of Particulate Concentration Indoors

The mass concentrations and time evolution of $PM_{0.7}$ and $PM_{2.5}$ aerosols were predicted for an office type indoor environment for a building located in an area where outdoor concentrations would be characterised by average values, such as identified from the measurements in run 1.

A schematic diagram of indoor space, HVAC system and input parameters used in the model are presented in Figure 3.

The modelling period from 6:00 a.m. to 6:00 p.m. was divided into 24–30-min time intervals. It was assumed that the concentration values for outdoor and indoor air remained constant during each of these intervals. The input data for outdoor concentrations during the day were based on $PM_{0.7}$ values presented in Figure 1.

The parameters for HVAC systems were selected in order to cover the most likely scenarios expected in real situations in the area of Brisbane. Based on a case-study conducted in an office building close to a freeway (Jamriska and Morawska, 1996), the input parameters were chosen, as follows: the ventilation rate (VR)=0.7 ach; R1=R2=0.1; and R3=9, where R1 and R2 parameters characterise the amount (ratio) of infiltrated an exfiltrated air compared to the amount of outdoor air delivered indoors. The R3 parameter represents the ratio between the flow rates for R/A and O/A. The presence of an indoor particle source, including occupants, could be incorporated into R1 by increasing its value, but was assumed to be negligible for these calculations (Jamriska et al., 1998a). The overall efficiency of an air-handling system in removing submicrometer particles (in the size range 0.016 to 0.700 micrometers) from supply air ($\varepsilon_{S/A}$) was set to be 34%

Table 1 Measured (SMPS) outdoor and predicted indoor aerosols mass concentration

	Aerosol mass concentration[a] ($\mu g \cdot m^{-3}$)			
	Air-handling system efficiency $\varepsilon_{S/A}$=34%		Air-handling system efficiency $\varepsilon_{S/A}$=85%	
	Maximum[b]	Average[b]	Maximum[b]	Average[b]
INDOOR AIR				
$PM_{0.7}$	32	16±9	5	2±2
$PM_{2.5}$	34	19±11	9	6±4
(estimated from AMRS data: $PM_{2.5}$=0.95 $PM_{0.7}$ + 4.05)				
$PM_{2.5}$	100	53±30	19	12−8
(estimated from Freeway data: ($PM_{2.5}$=2.97 $PM_{0.7}$ + 5.08)				
	Maximum[b]	Average[b]	Maximum[c]	Average[c]
OUTDOOR AIR				
$PM_{0.7}$	168	78±48	168	52±43

[a] Model's input parameters: R1=R2=0.1; R3=9; Ventilation Rate VR=0.7 [h^{-1}]
[b] Time interval: 6:00 a.m.–6:00 p.m.
[c] Time interval: 12:00 a.m.–12:00 p.m.

for deep bed throwaway Pyracube filters, and 85% for Electrostatic Ionitron Filters. These values are based on the results of previous studies as presented in more detail elsewhere (Jamriska and Morawska, 1996; Jamriska et al., 1998c). Filter performance was assessed according to the ASHRAE Standard 52.1–1992. Pyracube type of filters is commonly used in Australia in the HVAC systems employed in work related indoor environments; the electrostatic filters are used less frequently. The time evolution of indoor $PM_{0.7}$ for both sets of input parameters are presented in Figures 4 and 5, respectively. The figures show predicted mass concentrations of $PM_{0.7}$ (calculated from the model), and corresponding $PM_{2.5}$ mass concentrations calculated from $PM_{0.7}$ using the correlation factors discussed above.

It can be seen from Figures 4 and 5 that changes in indoor air mass concentrations followed changes in outdoor air concentrations during the day (Figure 1). The maximum values of $PM_{0.7}$ mass concentration were between 32 $\mu g \cdot m^{-3}$ (Figure 4, $\varepsilon_{S/A}$~34%) and 5 $\mu g \cdot m^{-3}$ (Figure 5, $\varepsilon_{S/A}$~85%). The concentration values averaged over the period from 6:00 a.m. to 6:00 p.m. were between 16±9 $\mu g \cdot m^{-3}$ and 2.4±1.5 $\mu g \cdot m^{-3}$ for the two filtration scenarios. The corresponding values of $PM_{2.5}$ concentrations are presented in Table 1.

The average mass concentration of $PM_{0.7}$ particles predicted for an indoor environment with the HVAC of low to medium efficiency ($\varepsilon_{S/A}$~34%) exceeded the annual US EPA $PM_{2.5}$ standard. The maximum value was comparable to the 24-h standard. The concentration levels estimated for $PM_{2.5}$ are up to three times higher (maximum 100 $\mu g \cdot m^{-3}$, average 53±30 $\mu g \cdot m^{-3}$), thus exceeding both the annual and the 24-h US EPA $PM_{2.5}$ standards. An application of a HVAC system with high filtration efficiency ($\varepsilon_{S/A}$~85%) significantly reduced the levels of predicted $PM_{0.7}$ mass concentration indoors with a maximum of about 5 $\mu g \cdot m^{-3}$, and the average values approximately 2.4±1.5 $\mu g \cdot m^{-3}$, for the 6:00 a.m.–6:00 p.m. period. This is well below the US EPA $PM_{2.5}$ standards, however the estimated $PM_{2.5}$ concentration, based on these values (maximum 19 $\mu g \cdot m^{-3}$; average 12±8 $\mu g \cdot m^{-3}$) may remain at a level comparable to the annual US EPA $PM_{2.5}$ standard.

It can be concluded that compliance with the US EPA $PM_{2.5}$ standards indoors, for a building located close to a busy traffic route, may depend mainly on the reduction efficiency of the HVAC system installed. A filtration system with an efficiency of up to 80 to 90% may be necessary to achieve indoor concentrations that comply with the ambient air standards.

In the absence of significant indoor particle sources, aerosol concentrations in naturally ventilated buildings are often comparable to outdoor air concentration levels. The indoor sources of aerosols are mostly associated with heating, gas stoves, food preparation and tobacco smoking and can significantly contribute to the concentration levels of fine particles (Wallace, 1996).

Conclusions

The results of this study indicate that exposure to $PM_{0.7}$ particles in ambient air close to a busy road exceeds the levels of the annual and 24-h US EPA $PM_{2.5}$ standards. It is likely that the exposure to $PM_{2.5}$ is even higher, and may significantly exceed these standards. The indoor exposure in a naturally ventilated building in a subtropical climate such as Queensland, is expected to be of similar, or higher, magnitude to exposure to ambient air outdoors. Indoor exposure in a building equipped with an air-handling system, is determined by the outdoor air concentrations and a system's particle reduction efficiency. The most dominant parameter of the reduction mechanisms is the filtration efficiency of the HVAC systems. To achieve compliance with new ambient US EPA $PM_{2.5}$ standards in indoor environments, it may be necessary to implement a filtration system of much higher efficiency than determined from present design guidelines.

Assessment of exposure to traffic related particles is an important issue due to its health implications. The work presented here was of limited scope and provided only an indication of the exposure levels for outdoor and indoor environments for specific conditions. A long-term study, of larger scope, targeting various traffic, meteorological and geographical conditions has been undertaken to provide more information on this broad topic.

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Appendix

Particle number balance equation:

$$V\frac{dC(t)}{dt}=(C_{O/A}.[Q_{O/A}.(1-\varepsilon_{S/A})+Q_{Inf}]+G)-C(t).(Q_{O/A}+Q_{Exf}+Q_{R/A}.\varepsilon_{S/A}) \quad (1)$$

A general solution:

$$C(t) = \frac{C_{O/A}.[Q_{O/A}.(1-\varepsilon_{S/A})+Q_{Inf}]+G}{Q_{O/A}+Q_{Exf}+Q_{R/A}.\varepsilon_{S/A}}.\left[1-exp\left(-\frac{Q_{O/A}+Q_{Exf}+Q_{R/A}.\varepsilon_{S/A}}{V}.t\right)\right]+C_o.exp\left[-\frac{Q_{O/A}+Q_{Exf}+Q_{R/A}.\varepsilon_{S/A}}{V}.t\right] \quad (2)$$

A general solution rewritten in simplified form (G-negligible)

$$C(t) = \frac{C_{O/A}.(1-\varepsilon_{S/A}+R_1)}{1+R_2+\varepsilon_{S/A}.R_3}.\left\{1-exp\left[-\frac{VR}{(1+R_3)}.(1+R_2+\varepsilon_{S/A}.R_3).t\right]\right\}+C_o.exp\left[-\frac{VR}{(1+R_3)}.(1+R_2+\varepsilon_{S/A}.R_3).t\right] \quad (3)$$

where

$\varepsilon_{S/A}$	– reduction efficiency of the air handling unit on supply air [–]
C_o	– initial particle concentration indoors [particle · m^{-3}]
$C_{O/A}$	– particle number concentration of outdoor air [particle · m^{-3}]
$C(t)$	– predicted particle number concentration indoors
G	– generation rate from indoor (people) sources [particle · s^{-1}]
R_1, R_2 and R_3	– ratios of the infiltrated, exfiltrated and return air flow rate to the outdoor air flow rate ($R_1=Q_{inf}/Q_{O/A}$; $R_2=Q_{Exf}/Q_{O/A}$, $R_3=Q_{R/A}/Q_{O/A}$)
$Q_{O/A}$, $Q_{R/A}$, Q_{inf}, Q_{Exf}	– outdoor, return, infiltrated, and exfiltrated air flow rate [$m^3 \cdot s^{-1}$]
V	– effective volume of the indoor space [m^3]
VR	– ventilation rate; $VR=Q_{S/A}/V$ [s^{-1}]