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Traffic-generated airborne particles in naturally ventilated multi-storey residential buildings of Singapore: Vertical distribution and potential health risks

M. Kalaiarasan [a,*], R. Balasubramanian [b], K.W.D. Cheong [a], K.W. Tham [a]

[a] *Department of Building, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566*
[b] *Division of Environmental Science and Engineering, Faculty of Enginering, National University of Singapore, 9 Engineering Drive 1, EA-03-12, Singapore 117566*

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ABSTRACT

The main objective of the study is to quantify the mass concentration exposure levels of fine traffic-generated particles ($PM_{2.5}$) at various heights of typical multi-storey public housing buildings located in close proximity, i.e. within 30 m and along a busy major expressway in Singapore. The secondary objective is to compare the potential health risks of occupants in the buildings, associated with inhalation exposure of fine traffic-generated particulate matter, based on estimated dose rates and the lowest observed adverse effect levels (loael) at the various floors of these buildings. Two typical public housing buildings, both naturally ventilated residential apartment blocks, of point block configuration (22-storey) and slab block configuration (16-storey) were selected for the study. Particulate samples were collected for both mass and chemical analysis (OC/EC ratio) at three representative floors: the lower, the mid, and upper floors of the buildings. Key meteorological parameters such as wind speed, wind direction, ambient temperature, and relative humidity were also concurrently measured at the sampling locations. For the potential health risk analysis, the occupants have been divided into four age categories namely, infants, children (1 year), children (8–10 years) and adults. The analysis takes into account age-specific breathing rates, body weights for different age categories. Experimental results explicitly showed that $PM_{2.5}$ mean particle mass concentration was highest at the midfloors of both buildings when compared to those measured at upper and lower floors during a typical day. Although the lower floors were closest to traffic emissions, the mean particle mass concentration was lower there than that at the midfloors, which could presumably be due to the interception of $PM_{2.5}$ particles by tree leaves or the inflow of clean and drier air from higher altitude with lower aerosol burden mixing with the traffic-polluted air at the lower levels thus lowering the concentration at the lower floors similar to induced chimney effect or both. The upper floors had the least fine particulate matter mass concentration due to dilution following pronounced mixing of traffic-polluted air with ambient air. The only difference between both blocks is that at corresponding floors, the mass concentration levels for slab block is much higher than that of point block. This could be attributed to the configuration of the blocks. Observational data show the slab block tends to slow down the approaching wind thus allowing the accumulation of the fine traffic-generated particulate matter in front of the building. For point block, the HR values at the mid and lower floors suggest that occupants living in these floors experience 1.81 and 1.34 times more health risk, respectively, in contracting respiratory diseases when compared to those living at the upper floors for all age categories. Similarly, for the slab block, occupants living in the mid and lower floors had 1.62 and 1.28 times more risk, respectively, in contracting respiratory diseases when compared to those living at the upper floors for all age categories.

1. Introduction

Motor vehicles produce a number of air pollutants that pose risks to human health. Some of the traffic-generated air pollutants are oxides of nitrogen (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and fine particulate matter ($PM_{2.5}$); $PM_{2.5}$, or fine particles, is the mass concentration of particles with aerodynamic diameters ≤ 2.5 μm. The health risk differs from one pollutant to another. For example, nitrogen dioxide (NO_2) mainly acts as an irritant affecting the mucosa of the eyes, nose, throat and the respiratory tract. On the other hand, fine particles can penetrate deep into the lungs and cause serious health problems such as irritation of the breathing airways, difficulty in breathing,

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[*] Corresponding author. Tel.: +65 65164599; fax: +65 67755502.
E-mail addresses: g0403455@nus.edu.sg (M. Kalaiarasan), eserbala@nus.edu.sg (R. Balasubramanian), bdgckw@nus.edu.sg (K.W.D. Cheong), bdgtkw@nus.edu.sg (K.W. Tham).

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aggravated asthma, development of chronic bronchitis and also premature deaths in people with heart or lung disease [1]. Consequently, this study is mainly focused on characterizing fine traffic-generated particles and assessing potential health risks associated with inhalation exposure.

Motor vehicle emissions constitute a main source of fine and ultrafine particles in urban area [2–7]. These tiny particles behave almost like gases and travel to the lower regions of the lungs. A study [8] reported that ultrafine particles in motor vehicle emissions have the largest surface area and the highest content of potentially toxic hydrocarbons among all particulate matter sources. Another study [9] reported that particle size, surface area, and chemical composition determine the health risk posed by particulate matter, and combustion particles such as from vehicle exhaust have a core of elemental carbon that is coated with a layer of chemicals, including organic hydrocarbons, metals, nitrates, and sulfates which may play a role in particle toxicity.

Particle size is an important factor that influences how particles deposit in the respiratory tract and affect human health. Coarse particles (particles larger than 2.5 μm and smaller than 10 μm in diameter) are deposited in the nose and throat, whereas fine and ultrafine particles generally are able to penetrate into deep areas of the lungs and cause serious respiratory problems. In Singapore, only PM_{10} (particles with aerodynamic diameters smaller than 10 μm) is monitored and the outdoor air quality standards of PM_{10} adopted is 150 $\mu g/m^3$ (24-h average) and 50 $\mu g/m^3$ (annual average). The USEPA national standards (NAAQS) for PM_{10} and $PM_{2.5}$ are 150 $\mu g/m^3$ and 35 $\mu g/m^3$ (24-h average), respectively and 15 $\mu g/m^3$ (annual average) for $PM_{2.5}$ [1]. In this study, particulate mass concentration was adopted although particulate matter number concentration appears to be a significant alternative to particulate mass concentration because, to the best of our knowledge, there are no air quality standards or health risk assessment procedures based on particulate matter number concentration yet. Most of the air quality standards and health risk assessment procedures are based on particulate matter mass concentration.

Currently, Singapore has a population of 4.68 million and is the fourth most densely populated country in the world. With a very high population density of 6369 persons/km^2 as at 2008 and a land area of 699.4 km^2, Singapore can be considered a land scarce country. The projected resident population is 6.5 million by 2020 [10]. Bronchial Asthma is one of the common respiratory disorders in Singapore. About 1 out of 5 children in Singapore are asthmatics and Singapore ranks number one in the Asia Pacific region in terms of the number of asthmatic kids between the ages 13 and 14 [11]. Almost 83% of the residents live in multi-storey public housing buildings which are mostly naturally ventilated [10]. Some of these multi-storey public housing buildings are located in close proximity to busy expressways, i.e. within 30 m from the expressways. With the expected increase in the population growth and in the motor vehicle numbers in Singapore, there is an increasing concern over both ambient and indoor air quality in the urban areas, especially in multi-storey public housing buildings located near expressways as on-road vehicles are main sources of fine traffic-generated particles in urban areas. The fine traffic-generated particles could be inhaled by building occupants and thus this could affect their health over time. Consequently, there is a strong need for carrying out health risk assessment studies in Singapore, which has citizens suffering from serious pollution-related health problems.

There is however a lack of comprehensive data on the vertical distribution profile of fine traffic-generated particulate matter with respect to the different floor heights in naturally ventilated multi-storey public housing buildings located in close proximity to busy expressways in the tropics. The few available studies on buildings located near expressways dealt primarily with the vertical distribution profile of traffic-generated particles in buildings that were air-conditioned (office) and were located in cities or in street canyons with either dry, subtropical, or temperate climatic conditions. For example, Morawska et al. [12] found no significant height dependence of particle number concentration for an office block from 3rd to 25th floor which was located 80 m from the motorway in Brisbane, Australia. However, for a building located 15 m from motorway, they found the particle number concentration at the building envelope was very high comparable to those in the immediate vicinity of the motorway. Wu et al. [13] observed at the building height of 79 m, the mass concentration levels of PM_1, $PM_{2.5}$, and PM_{10} decreased to about 80%, 62% and 60% respectively, of the maximum concentration level occurring at 2 m from the ground in Macau, China. Other investigators including Rubino et al. [14] of Italy, Hitchins et al. [15] of Australia, Chan and Kwok [16] of Hong Kong have also found that particle mass/number concentrations decreased with increasing height of a building. It is therefore critically important to conduct field-based investigation in the tropics to gain a better understanding of the relationship between the vertical transport of fine traffic-generated particulate matter and their potential health impacts on the indoor air quality in naturally ventilated multi-storey public housing buildings. Researchers [17,18] have shown that outdoor particulate matter concentration levels could be used to predict indoor concentration levels. Previous studies in Singapore [19] have reported that the indoor/outdoor (I/O) ratio in naturally ventilated building is close to unity.

This paper reports the vertical distribution profiles of fine traffic-generated particulate matter in two typical naturally ventilated multi-storey public housing buildings, point and slab block configurations, in Singapore for the first time. Air sampling was conducted under the influence of predominant Southeast monsoon wind which was blowing perpendicular to the building façade. Both the buildings selected were located within 30 m, on the downwind side of a very busy expressway. The buildings were located about 300 m apart, shoulder-to-shoulder from each other. The results obtained from this comprehensive study are discussed. In addition, a comparison is made between the potential health risks of occupants in the buildings associated with inhalation exposure of the fine traffic-generated particulate matter, based on estimated dose rates and the lowest observed adverse effect levels (loael) at the various floors of these buildings.

2. Methodology

Chemical analysis was only performed on 24-h samples at the measured floors to confirm that the $PM_{2.5}$ originates from the on-road vehicles and not from fugitive dust re-entrained by the eddies of the traffic. Data on carbonaceous species, organic carbon (OC) and elemental carbon (EC), were obtained and the ratio between these species, i.e. OC/EC ratio is evaluated for real traffic emissions. It has been reported [20] that a value of 3.7 was expected for the OC/EC in traffic emissions. Giugliano et al. [21] reported a lower value of $OC/EC = 1.34$ in an urban tunnel of Milan suggesting the circulating fleet in the city was dominated by catalyzed vehicles.

2.1. Site characterization and sampling strategy

The Central Expressway (CTE) is one of the most highly utilized expressways which link many residential towns to the Central Business District of Singapore. The expressway is a dual carriageway with each carriageway having 3 lanes. Two typical naturally ventilated multi-storey public housing buildings from the same site, one point and the other slab block configurations were selected due to their close proximity to the CTE as they were located within 30 m and on the downwind side of the expressway as shown in Figs. 1 and 2. Both the concrete buildings were about 30 years old and were located about 300 m apart, shoulder-to-shoulder from each other. The schematic illustration of the locations and characteristics of sampling sites is shown in Fig. 3. The ground on which both buildings stood was reasonably flat. The actual dimensions of the point and slab blocks were 23.82 m (L) × 23.71 m (W) × 52.87 m (H) and 126.90 m (L) × 12.57 m (W) × 42.40 m (H), respectively. Each storey height is about 2.80 m for both the buildings. The point block was 'H' shaped and had 4 homes in each horizontal storey with 2 homes, with their living rooms south-east facing, i.e. towards the expressway while the other two is north-west facing whilst the slab block was rectangular and had 12 homes, in each horizontal storey with their living rooms south-east facing. The number of occupants in each apartment varied from 3 to 5. The trees planted along the expressway were single row and had drooping branches with dense and complex canopy structure. The average tree canopy height spanned from near ground level to about 3½ to 4 storey high. Fronting the tree canopy was 1 m tall hedges which was about 0.7 m wide. The wind was blowing in the Southeast direction perpendicularly towards the building facades which tended to advect most of the traffic pollutants towards the buildings. On the opposite side of the expressway (upstream direction), the nearest building apartment was about 500 m away from the measurement site. Street–canyon effect was considered negligible in this study. All the measurements were taken on hot and sunny clear days.

Particulate samples for mass and chemical analysis (OC/EC ratio) were collected from three representative floors each representing the lower, the mid, and upper floors of each building and at the upstream of the sampling site to determine the upstream background concentration levels. For both the blocks, the vertical distribution of particulate matter was obtained at the middle of the buildings. Figs. 1 and 2 show the locations of instruments. The instruments were placed 1.5 m high (breathing zone) from the floor in the building's outdoor corridor or balcony, at least 1 m away from the parapet wall of the building as recommended by manufacturer. All the measurements were made at the windward face of the building and were strategically located to allow free flow of outdoor air laden with particulate matter which subsequently penetrates into the homes of the buildings. Outdoor measurements were taken because based on the previous studies in Singapore [19], it was reported that the I/O ratio in naturally ventilated building was close to unity suggesting pollution migration was from outdoors to indoors rather than its emission from within internal sources. Key meteorological parameters such as wind speed, wind direction, ambient temperature, and relative humidity were also concurrently measured at the same sampling locations. The frequency of measurement was 5 min average readings in the case of meteorological parameters while it was 24 h for the particulate concentration levels. Wind speed and direction were measured from 10 am to 10 pm daily while ambient temperature and relative humidity were measured for 24 h daily. Cross calibration checks between the various instruments used were performed continuously for a week before the measurement commenced. This was done in a controlled environment. The difference between the readings of the respective instrument was less than 5%. Calibration checks of the instruments were also performed before and after each measurement day.

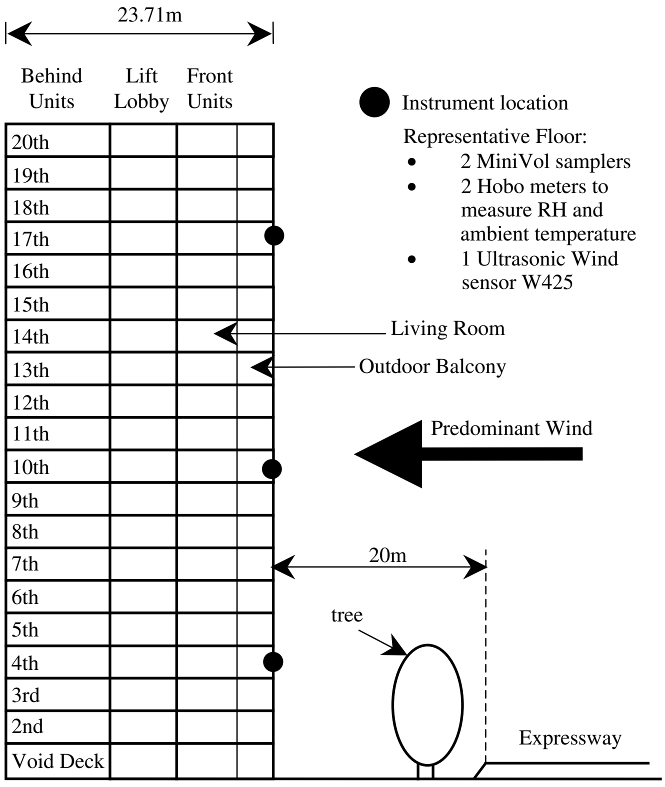

Fig. 1. End elevation of naturally ventilated point block.

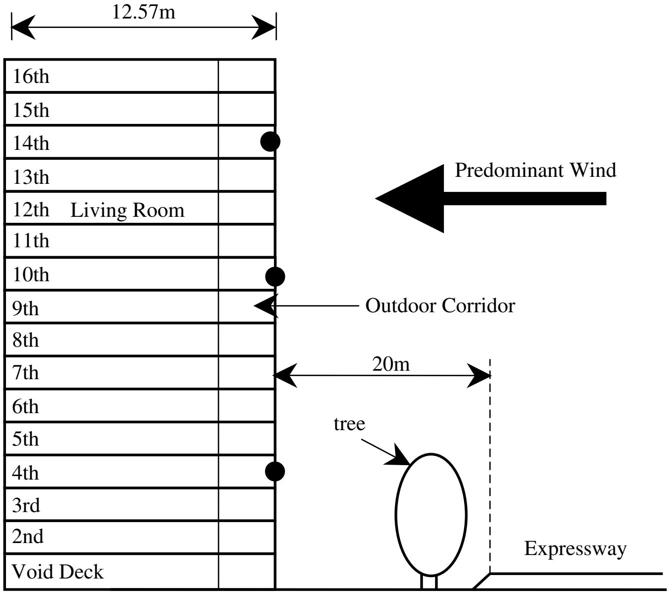

Fig. 2. End elevation of naturally ventilated slab block.

The particulate samples were collected using portable, battery-operated low volume samplers (MiniVol). Generally, the low volume sampler shows smaller values than a standard high volume sampler. The difference in mass concentration of particles collected ($PM_{2.5}$) by a low volume sampler could be as much as 12% lesser than that of a high volume sampler. This difference could be due to different inlet systems (virtual impactors), different filter material used etc. [22]. The samplers draw air continuously for 24 h through a 47-mm PTFE/QMA quartz fiber filter at a pre-calibrated flow rate of 5 l/min via a $PM_{2.5}$ inlet. The PTFE samples were used for the determination of mass concentration values while pre-combusted QMA quartz fiber samples were used for EC and OC analysis. The air flow rates were checked before and at the end of each measurement to ensure that a constant flow rate was maintained throughout the sampling period. Field blanks were collected in all the representative floors to determine any potential background contamination during sampling, transport and storage. A total of 80

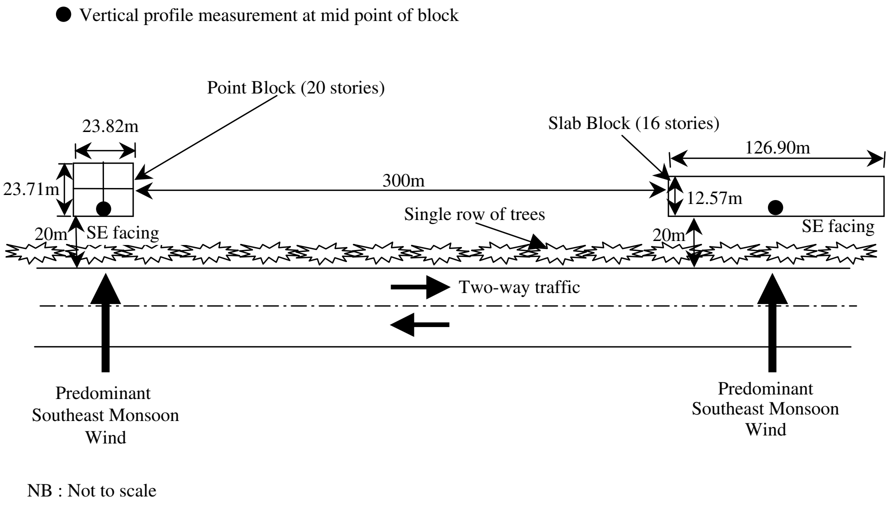

Fig. 3. Schematic illustration of the locations and characteristics of sampling sites.

PTFE (60 samples from the building and 20 samples from the background site) and 80 QMA quartz fiber samples (60 samples from the building and 20 samples from the background site) were collected for each block. The filters were weighed with MC-5 microbalance (Sartorius AG, Goettingen, Germany) with 1 μg sensitivity before and after sampling. The microbalance was calibrated with a primary standard traceable to NIST mass standard. Humidity meters were used to record the ambient temperature and relative humidity. The instruments have in-built data loggers and can measure temperature with an accuracy of ±0.7 °C at 21 °C and RH with an accuracy of ±5% RH. The wind speed and wind direction were obtained using ultrasonic wind sensor. The instruments have an accuracy of ±2° for wind direction and ±0.135 m/s for wind speed magnitude. The measurements were conducted for one month continuously (2 July to 27 July 2007) during which the island experienced the predominant southeast monsoon winds which tend to transport the traffic-generated particulate matter from the expressway to the residential apartments. The measurement period did not include weekends.

2.2. *Traffic measurement*

The traffic data obtained were recorded continuously by the Land Transport Authority of Singapore (LTA). The traffic count was made with the help of an intelligent management system that monitors and manages traffic along expressways, through cameras mounted on lamp posts. The cameras were located in front of the blocks and captured the traffic on the expressway. The number of vehicles on road was counted on an hourly basis for a period of 24 h.

2.3. *Gravimetric analysis of filters*

The filters were pre-equilibrated in a temperature of 25.00 ± 0.50 °C and relative humidity of 35.00 ± 3.00% controlled environment for at least 24 h before the actual weighing. Mass concentrations were then calculated using the actual weight of the particulates collected. This was obtained by subtracting the pre-collection weight from post-collection weight. The weight was then divided by the volume of air that was pulled through the filter (μg/m^3) over the sampling period to obtain the mass concentration. After the gravimetric analysis, QMA quartz fiber field blanks and sample filters, were transferred to individual petri-slides and stored at 4 °C until extraction and subsequent analysis. This is done to prevent loss of semi-volatile organic carbon. All procedures were strictly quality-controlled to avoid any possible contamination of the samples.

2.4. *Chemical analysis of carbonaceous species in PM$_{2.5}$*

In this study, only EC and OC results were discussed since OC/EC ratio could be used to evaluate for real traffic emissions. The total carbon (TC) can be categorized as the sum of organic carbon (OC), elemental carbon (EC), and inorganic carbon (IC). The differential forms of carbon (TC, EC, IC and OC) were analyzed using the elemental CHN 2400 analyzer. The details of experimental procedure for their determination are described elsewhere [23,24]. Briefly, TC was determined following the multipoint calibration of the elemental analyzer with acetanilide as a reference standard. After removal of IC from filter, this amount was deducted from that of TC. The resultant mass of carbon is now due to both EC and OC (TC minus total inorganic carbon (TIC)). For EC measurement, the filter is placed in a crucible and heated in a Carbolite Oven at 350 °C for 24 h for both IC and OC compound removal. EC amount is then determined using the CHN analyzer. The amount of OC was obtained by the difference [TC – TIC – EC]. The detection limits of TC, EC, and OC were 0.03, 0.03, and 0.06 μg/m^3 respectively.

2.5. *Health risk analysis*

The analysis of the potential health risk of occupants associated with inhalation exposure of traffic-generated particulate matter in the buildings was based on estimated the dose rates and the lowest observed adverse effect levels (loael) at the various floors of these buildings. Loael is defined as the lowest tested dose of a pollutant that has been reported to cause harmful (adverse) health effects on people or animal. Exposure occurs when a person comes in contact with a pollutant [25]. Dose occurs only when the pollutant crosses the physical envelope representing the person. The analysis is age-specific, and it divides the occupants under four age-specific categories namely, new born, children (1 year), children (8–10 years) and adults. The dose rate of fine traffic-generated particulate matter has been estimated through the following expression over a day [26].

$$\text{Dose rate}(D) = [\text{BR}/\text{BW}]\int_0^{24} C(t)\text{OF}(t)\text{d}t \tag{1}$$

where D is the age-specific dose rate (μg/kg); BR is age-specific breathing rate (L/min); BW is age-specific body weight (kg); $C(t)$ is diurnal concentration of the pollutant (μg/m^3); and OF(t) is occupancy factor (percentage of residents likely to be in the building at a given interval of time).

For the estimation of the potential health risks of occupants due to inhalation of fine traffic-generated particulate matter, the following expression was used.

$$\text{Health risk} = [\text{Dose rate}/\text{loael}] \qquad (2)$$

HR is dimensionless and useful for making relative comparisons. Since there are no data in Singapore on age-specific breathing rates, age-specific body weights, and loael values for morbidity, these values reported by Cerna et al. [27] were used as shown in Table 1.

2.6. Quality control and quality assurance

All filters used in this study were inspected for defects under bright illumination before exposure. Filters are installed in the low volume samplers using Teflon-tipped forceps. Soon after the end of the sampling period, exposed filters were retrieved to avoid potential for filter damage, or changes in sample mass due to particle loss, passive deposition, or volatilization increases if the filter was left in the sampler for extended periods. The microbalance used to obtain the particulate mass had 1 μg sensitivity, and was maintained at a relative humidity of 35.0 ± 3.0%. The microbalance was calibrated to NIST mass standards at the beginning of each weighing session.

Field blanks (PTFE and QMA quartz fiber filters) were collected in all the representative floors and background locations to determine any potential background contamination during sampling, transport and storage. They were removed during the deployment interval and were placed in air tight containers before returning them to the laboratory for testing. They were treated as regular samples. The field blanks accounted for 50% of total number of PTFE and QMA quartz fiber samples collected for each block. The mass concentration in the field blanks accounted for less than 1% of the corresponding mass concentrations of the PTFE and QMA quartz fiber samples. All the samples were corrected for potential background contamination during sampling, transport, and storage.

For the carbon analysis using the CHN analyzer, a standard (acetanilide) was combusted for every 5 samples to check the accuracy of the analysis. Although there is no absolute standard available to assess the accuracy of carbon measurements, the results obtained were highly reproducible. For OC and EC, the average precision of the measurements based on repeated analysis of calibration standards was ±6% and ±5%, respectively.

2.7. Statistical analysis (Student's t-test)

The t-test assesses whether the means of two groups are statistically different from each other in relation to the variation in the data. It is applied when sample sizes are small enough that using an assumption of normality leads to incorrect inference. The t-test and one-way Analysis of Variance (ANOVA) are mathematically equivalent and would yield identical results.

Table 1
Breathing rates, body weights, and loael values for morbidity.

Age group	Inhalation volume (m^3/day)	Body weight (kg)	Loael for morbidity (μg/kg per day)
Adult	20	70	15.7
Children 8–10-year-old	10	30	27.5
Children 1-year-old	3.8	10	20.9
New born	0.8	3	14.7

Source: Cerna et al. [27].

3. Results and discussion

3.1. Traffic volume

The contribution of the various types of motor vehicles to the total fine traffic-generated particulate matter was not quantified in this study. The traffic counts obtained for both the blocks were the same and were representative of the traffic outside each of the building. The traffic composition analysis indicated that petrol-driven passenger cars fitted with catalytic converters were the major contributor to traffic counts (about 60%). Results showed that traffic pattern on all days of a week had similar trend. Traffic counts started to rise between 1000 and 1300 hours, before reaching maximum traffic count during 1300–1700 hours. Traffic counts then decreased between 1700 and 2000 hours. The decrease in traffic counts during this time could be due diversion of vehicles towards other alternative routes as the ERP gantry operates during 1800–2000 hours. Traffic counts then started to increase again between 2000 and 2200 hours. The daily traffic volume ranged from 14,000 to 17,000 vehicles/h. The average daily traffic volume was 15,500 ± 1200. The average traffic volume during 1000–1300 hours can be as many as 15,000 vehicles/h. Thereafter, from 1300 to 1700 hours, the average quantity of cars remains fairly constant at about 15,000–17,000 vehicles/h. Approaching the end of the day, the traffic condition worsens, leading to congestion with cars moving at low speed. The average volume of traffic during 1700–2200 hours was about 13,500 vehicles/h.

3.2. Wind direction and wind speed

The wind direction measurements showed that the south-eastern monsoon winds were the dominant winds blowing at right angles towards the building façade where the living room was located. These prevailing weather conditions facilitated the transport of the fine traffic-generated particulate towards the residential apartments. Daily wind speed and direction were measured from 10 am to 10 pm during the measurement period. The overall mean wind speed was 1.75 ± 0.45 m/s and 1.36 ± 0.42 m/s for the point block and slab blocks respectively. The mean wind speed at the lower floor was 1.65 ± 0.49 m/s, 1.73 ± 0.32 m/s for midfloor and 1.91 ± 0.47 m/s for upper floor for point block and for slab block, the mean wind speed at the lower floor was 0.68 ± 0.37 m/s, 1.49 ± 0.40 m/s for midfloor and 1.72 ± 0.39 m/s for upper floor. Generally, the mean wind speed increased with height of the buildings.

3.3. Temperature and relative humidity

Ambient temperature and relative humidity were measured for 24 h daily during the measurement period. The overall mean temperature was 29.9 ± 2.7 °C and 30.2 ± 3.1 °C for the point and slab block, respectively. The mean temperature at the lower floor was 30.2 ± 3.5 °C, 29.7 ± 2.5 °C for midfloor, and 29.4 ± 3.2 °C for upper floor for point block and for slab block, the mean temperature at the lower floor was 30.5 ± 2.7 °C, 30.1 ± 2.9 °C for midfloor, and 29.8 ± 3.6 °C for upper floor. The temperature difference between each floor at any one time did not exceed 0.8 °C for both the blocks. The overall mean relative humidity was 71.7 ± 4.7% and 69.1 ± 4.1% for the point and slab blocks, respectively. The mean relative humidity was 69.2 ± 3.9% at the lower floor, 72.8 ± 4.2% at the midfloor, and 73.4 ± 3.2% at the upper floor for the point block while they were 65 ± 4.6% at the lower floor, 68.1 ± 4.9% at the midfloor, and 70.3 ± 4.4% at the upper floor for the slab block. The difference in relative humidity between each floor at any one time did not exceed 5% for both the blocks. For both blocks, the vertical temperature distribution profile and relative humidity distribution profile showed very little stratification between the three selected floors. The low relative humidity and temperature stratification observed between the three selected floors could be due to rapid mixing of air near the boundary layer of the building thus resulting in very small vertical stratification in both relative humidity and temperature. Because of the very little temperature stratification between the three selected floors of both the buildings, buoyancy effects on the transportation of fine traffic-generated particulate matter can be considered negligible.

3.4. Chemical analysis of carbonaceous species in $PM_{2.5}$

The mean daily upstream background levels for OC and EC were $5.83 \pm 2.61\ \mu g/m^3$ and $6.65 \pm 1.83\ \mu g/m^3$, respectively. The mean EC and OC mass concentrations at the various floors of point and slab blocks are shown in Table 2. There was a significant difference between upstream and those EC and OC values measured at the various floors of both the blocks ($p < 0.02$ for OC and $p < 0.04$ for EC for point block and $p < 0.03$ for OC and $p < 0.02$ for EC for slab block). This indicated most of the particulate matter measured at the floors was from the traffic since motor vehicle emissions mainly consisted of elemental and organic carbon particles. For point and slab blocks, the overall mean OC/EC ratio for the various floors was 1.59 ± 0.23 (1.20–1.81) and 1.67 ± 0.31 (1.04–1.73) respectively. Values in bracket indicate the range of OC/EC ratio values for all days at the different floors of the buildings. This was within the expected value of 3.7 for traffic emissions [20] and the lower values obtained in this study suggested the expressway was dominated by vehicles with catalytic converter [21].

3.5. Vertical distribution profile of fine particulate matter

Experimental results explicitly showed that $PM_{2.5}$ mean particle mass concentration was highest at the midfloors of both buildings when compared to those measured at upper and lower floors during a typical day as shown in Table 3. Although the lower floors were closest to traffic emissions, the mean particle mass concentration was lower there than that at the midfloors, which could presumably be due to the interception of $PM_{2.5}$ particles by tree leaves [28,29] or the inflow of clean and drier air from higher altitude with lower aerosol burden mixing with the traffic-polluted air at the lower levels thus lowering the concentration at the lower floors similar to induced chimney effect or both. The lower dew-point temperatures measured at lower floors of the both the blocks suggest inflow of drier air from higher altitudes. Vegetation and trees could have obstructed and uphold the predominant wind at the lower floors resulting in the downdraughting of cleaner air from the shadow side of the building towards the measurement location at the lower floor. More research is currently being done to investigate the windflow pattern using CO as a tracer gas as CO measurements could serve as indicator for establishing whether the traffic-polluted air has been mixed with cleaner air when it arrives at the sampling locations. The upper floors had the least fine particulate matter mass concentration due to dilution following pronounced mixing of traffic-polluted air with ambient air. The vertical distribution profile of $PM_{2.5}$ mass concentration in this study contradicts the vertical distribution profile of several studies which found that particulate matter concentration level usually decreased with increasing height [13–16]. The buildings used in the previous studies were mainly air-conditioned. In this study, microclimatic conditions of the selected site, such as the influence of trees, could have had an influence on the vertical distribution profile of particulate matter. The only difference between both blocks is that at corresponding floors, the mass concentration levels for slab block are much higher than that of point block. This could be attributed to the configuration of the blocks. The observational data show the slab block tends to slow down the approaching wind, thus allowing the accumulation of the fine traffic-generated particulate matter in front of the building.

Table 3
Mean particle mass ($PM_{2.5}$) in point block (PB) and slab block (SB) for a typical working week (point block).

Day		Upstream background level ($\mu g/m^3$)	4th Floor ($\mu g/m^3$)	10th Floor ($\mu g/m^3$)	14th/17th Floor ($\mu g/m^3$)
1	PB	22.11 ± 4.92	45.63 ± 5.31	62.17 ± 6.12	33.36 ± 3.99
	SB	24.25 ± 3.96	58.49 ± 4.46	73.87 ± 5.08	45.32 ± 5.42
2	PB	23.67 ± 5.24	48.75 ± 4.06	61.48 ± 5.03	35.63 ± 4.28
	SB	22.98 ± 4.53	60.28 ± 5.51	75.91 ± 4.96	50.01 ± 4.67
3	PB	20.78 ± 4.15	36.80 ± 4.92	49.33 ± 4.41	26.97 ± 3.36
	SB	23.67 ± 4.99	52.67 ± 4.95	65.39 ± 4.15	41.33 ± 5.06
4	PB	22.98 ± 3.96	37.25 ± 4.76	53.91 ± 5.63	28.36 ± 4.14
	SB	24.01 ± 5.07	51.76 ± 5.19	66.83 ± 4.29	40.03 ± 3.93
5	PB	23.96 ± 4.53	39.11 ± 5.77	54.14 ± 4.19	30.69 ± 4.58
	SB	22.83 ± 4.45	53.55 ± 5.77	68.76 ± 4.07	39.95 ± 4.98

3.6. Health risk assessment

Dose rates and HR values for both the blocks are shown in Tables 4 and 5. The results were calculated based on the outdoor values

Table 2
Mean EC and OC mass concentration in point block (PB) and slab block (SB) for a typical working week.

Day		$n = 80$ EC			1.4^{*}OC		
		4th Floor ($\mu g/m^3$)	10th Floor ($\mu g/m^3$)	14th/17th Floor ($\mu g/m^3$)	4th Floor ($\mu g/m^3$)	10th Floor ($\mu g/m^3$)	14th/17th Floor ($\mu g/m^3$)
1	PB	16.58 ± 2.17	21.58 ± 3.02	11.79 ± 2.94	19.31 ± 3.31	30.98 ± 3.68	15.98 ± 2.10
	SB	19.63 ± 3.12	26.65 ± 2.17	16.53 ± 1.75	27.37 ± 2.43	36.31 ± 3.91	21.26 ± 3.18
2	PB	17.39 ± 3.21	20.89 ± 2.56	12.33 ± 1.89	20.87 ± 2.26	29.98 ± 3.01	16.96 ± 2.66
	SB	21.71 ± 2.97	27.32 ± 1.95	18.01 ± 2.26	28.79 ± 3.85	37.56 ± 3.77	23.27 ± 2.89
3	PB	12.54 ± 2.16	17.60 ± 2.92	8.98 ± 1.71	16.42 ± 2.02	22.67 ± 2.36	12.24 ± 1.95
	SB	17.37 ± 3.09	22.53 ± 2.44	14.49 ± 2.22	24.49 ± 1.99	32.61 ± 2.55	19.24 ± 1.95
4	PB	12.96 ± 2.11	18.96 ± 3.09	9.21 ± 2.54	17.63 ± 1.98	25.63 ± 3.44	13.91 ± 2.82
	SB	17.85 ± 2.82	22.87 ± 2.81	13.91 ± 3.17	23.55 ± 2.48	32.83 ± 2.09	20.42 ± 2.09
5	PB	13.16 ± 1.57	18.23 ± 2.54	9.86 ± 1.39	18.42 ± 2.75	26.96 ± 3.08	15.03 ± 2.17
	SB	18.87 ± 2.33	23.30 ± 3.02	12.85 ± 2.48	26.03 ± 3.32	34.45 ± 2.67	20.11 ± 3.02

n = Number of samples collected and analyzed for mass concentration.

Table 4
Dose rates and HR values for point block.

Floor	$n = 80$ Dose rate (μg/kg)				HR (dimensionless)			
	New born	Children (1 year)	Children (8–10 years)	Adult	New born	Children (1 year)	Children (8–10 years)	Adult
Lower floor	7.68 ± 1.00	10.95 ± 1.42	9.61 ± 1.24	8.24 ± 1.06	0.51 ± 0.06	0.52 ± 0.07	0.36 ± 0.04	0.54 ± 0.05
Midfloor	10.41 ± 1.02	14.83 ± 1.45	13.01 ± 1.27	11.15 ± 1.09	0.70 ± 0.07	0.72 ± 0.04	0.47 ± 0.05	0.71 ± 0.06
Upper floor	5.74 ± 0.66	8.18 ± 0.94	7.18 ± 0.82	6.15 ± 0.70	0.39 ± 0.04	0.38 ± 0.05	0.26 ± 0.03	0.40 ± 0.04

n = Number of samples collected and analyzed for mass concentration.

Table 5
Dose rates and HR values for slab block.

Floor	$n = 80$ Dose rate (μg/kg)				HR (dimensionless)			
	New born	Children (1 year)	Children (8–10 years)	Adult	New born	Children (1 year)	Children (8–10 years)	Adult
Lower floor	10.25 ± 0.70	14.61 ± 1.00	12.81 ± 0.88	10.98 ± 0.75	0.70 ± 0.04	0.69 ± 0.05	0.47 ± 0.03	0.68 ± 0.07
Midfloor	12.99 ± 0.84	18.51 ± 1.20	16.24 ± 1.05	13.92 ± 0.90	0.88 ± 0.06	0.86 ± 0.04	0.59 ± 0.04	0.89 ± 0.03
Upper floor	8.02 ± 0.80	11.43 ± 1.14	10.03 ± 1.00	8.60 ± 0.86	0.55 ± 0.05	0.53 ± 0.07	0.36 ± 0.05	0.56 ± 0.04

n = Number of samples collected and analyzed for mass concentration.

since the I/O ratio of naturally ventilated buildings in Singapore as obtained in previous study was close to unity [19]. The analysis shows that the potential health risks to respiratory disease are highest for all age categories in the midfloors of both the buildings compared to the upper (lowest) and lower floors (second highest). New born babies, one-year-old children, and adults had similar potential health risk while teenage children of ages between eight and ten years old had the lowest potential health risk for both the blocks. For the point block, the HR values at the mid and lower floors indicate that occupants living in these floors had 1.81 and 1.34 times more risk, respectively, in terms of developing respiratory diseases when compared to occupants living at the upper floors for all age categories. Similarly, for the slab block, occupants living in the mid and lower floors had 1.62 and 1.28 times more risk, respectively, in terms of developing respiratory diseases when compared to occupants living at the upper floors for all age categories.

The HR values are most likely to increase since the vehicle population in Singapore keeps on increasing over the years from 683,204 vehicles in 1997 to 851,336 vehicles in 2008 [10]. Given that the projected population growth will increase by about 50% and more residential buildings will be constructed to provide accommodation for new residents, it is important to consider the possible penetration of fine traffic-generated particulate into buildings at the design stage proactively.

4. Conclusion

This study clearly showed that $PM_{2.5}$ mean particle mass concentration was highest at the midfloors of both buildings when compared to those at upper and lower floors during a typical day. Although the lower floors were closest to traffic emissions, the mean particle mass concentration was lower there than that at the midfloors, which could presumably be due to the interception of $PM_{2.5}$ particles by tree leaves or the inflow of clean and drier air from higher altitude with lower aerosol burden mixing with the traffic-polluted air at the lower levels or both. The upper floors had the least fine particulate matter mass concentration due to dilution following pronounced mixing of traffic-polluted air with ambient air. Microclimatic conditions of the selected site such as the influence of trees could have had an influence on the vertical distribution profile of particulate matter. The only difference between both blocks is that at corresponding floors, the mass concentration levels for the slab block is much higher than that of the point block. This could be attributed to the configuration of the blocks. Observational data show the slab block tends to slow down the approaching wind thus allowing the accumulation of the fine traffic-generated particulate matter in front of the building. For the point block, the HR values at the mid and lower floors indicate that occupants living in these floors had 1.81 and 1.34 times more risk, respectively, in contracting respiratory diseases when compared to occupants living at the upper floors for all age categories. Similarly, for slab block occupants living in the mid and lower floors had 1.62 and 1.28 times more risk, respectively, in contracting respiratory disease when compared to occupants living at the upper floors for all age categories. The study showed the point block is a better design compared to the slab block in terms of mitigating the penetration of the ambient fine traffic-generated particulate matter into the indoor environment. A good façade design could further mitigate the penetration of the ambient fine traffic-generated particulate matter indoors.

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