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Pedestrian Exposure to Ultrafine Particles in Hong Kong Under Heavy Traffic Conditions

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Abstract

Vehicle generated particle emissions represent a major source of air pollution in urban environments. Recent studies show that monitoring particulate matter in the ultrafine particle (UF) size range (diameter < 100 nm) is critical for assessing adverse health effects. A consensus is emerging that particle number concentration, rather than particle mass, may constitute a better predictor of health effects resulting from exposure to particulate matter (Oberdorster *et al.*, 1990; Pekkanen *et al.*, 1997; Peters *et al.*, 1997; Laden *et al.*, 2000). In this study, a water-based condensation particle counter (WCPC) was used to measure particle number concentrations at a busy intersection of Lai Chi Kok Road and Nathan Lane, located in the center of the urban mega city Mong Kok of Kowloon, Hong Kong. Individual particle numbers and traffic patterns revealed that spikes in the particle number concentration coincided with vehicle acceleration. The highest average particle count (~9.0×10^4 particle/cm^3) was observed in an area next to the Hong Kong Environmental Protection Department measurement station (*Site A*), followed by ~5.5×10^4 particle/cm^3 measured at the roadside walkway at the Pioneer Shopping Center (*Site B*), and ~4.5×10^4 particle/cm^3 in front of the SKH Kei Wing primary school (*Site C*). The highest particle counts occurred when vehicles accelerate, after stopping at a signal light or a bus stop; a peak concentration of 5.4×10^5 particle/cm^3 was observed during acceleration of a heavy-duty diesel bus. Peaks with particle number similar to this were reported for a Los Angeles freeway which has the highest percentage (25%) of diesel vehicles (Zhu *et al.*, 2007).

Keywords: Ultrafine particles; Pedestrian exposure; Particle number concentration, Water-based CPC; Hong Kong.

INTRODUCTION

Gasoline and diesel vehicle engine exhaust constitute a major source of ultrafine (UF, dp < 100 nm) particulate matter (PM) in urban areas. Ultrafine particles can enter the circulatory

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system and are capable of causing both acute and chronic adverse health effects (Nemmar *et al.*, 2002; Donaldson and Stone, 2003; Oberdorster *et al.*, 1990). Studies have shown that particles in the UF size range are able to penetrate cellular organelles such as mitochondria (Li *et al.*, 2003; Li *et al.*, 2004). Measurements at a major Los Angeles freeway showed that the concentration of smaller UF particles can be up to 25 times greater than ambient counts (Zhu *et al.*, 2002a, b). A study of in-cabin passenger exposure to UF particles on Los Angeles roads and freeways revealed dramatic increases in particle number concentration from nearby vehicle exhaust (Miguel et al., 2003), and that particle size distributions, observed both in-cabin and on road, were bi-modal with diameters around 10-20 nm and 50-70 nm (Zhu et al., 2007). Since the majority of Hong Kong's urban population spends time outdoors as pedestrians close to high volume of traffic, quantitative knowledge is needed regarding the extent of their exposure to vehicular UF particles that may cause adverse health effects.

The Hong Kong Environmental Protection Department (HKEPD) operates an air quality monitoring station measuring various pollutants at the intersection of Lai Chi Kok Road and Nathan Lane. However, the respirable suspended particulate matter (RSP) measurements taken by this station are dependent on *mass* concentrations whereas increasing detrimental health effects are better correlated to decreasing particle size (Dockery *et al.*, 1993; Pope *el al.*, 1995) and hence particle number concentration. In this paper we report on measurements of particle number concentration (number/cm^3) with aerodynamic diameters in the ~5 nm to ~2 µm size range, made at three locations at the Lai Chi Kok intersection in Mongkok: (i) next to the HKEPD roadside monitoring station, (ii) on the sidewalk of a shopping mall building, and, (iii) at the front door of a primary school while classes were in session. The major objective of this study was to evaluate the exposure of pedestrians to vehicular emissions of UF particles, while walking near several high volume pedestrian walkways, in an area of high vehicular traffic volume.

EXPERIMENTAL METHOD

A water-based condensation particle counter (WCPC, TSI Inc. Model 3785, Saint Paul, MN) was mounted on a mobile platform at a height of 1.0 m from the ground. WCPC data were collected in 1-second intervals to provide high resolution temporal results. Power was supplied by a deep cycle 12 V battery and inverter to run the WCPC (Hering and Stolzenburg 2005a; Hering et al., 2005b) and a laptop. A 5 cm length of copper tubing (0.635 cm dia.) pointed towards the road was used to collect samples. Data acquisition was performed on site and in real-time with a laptop computer running the 32-bit TSI (2005) Aerosol Instrument Manager, a program that permits instrument control and data collection, management, and export capabilities.

The measurements were conducted in central Kowloon, Hong Kong near several high volume pedestrian walkways around the intersection of

Nathan Lane and Lai Chi Kok road. Nathan Lane and Lai Chi Kok road each have 6 lanes, 3 in each direction. Like much of Hong Kong, the intersection is a street canyon bounded on all sides by high-rise commercial and residential buildings. Due to this, wind patterns in the immediate vicinity of the intersection are complex. Air movement was generated by the vehicle traffic as opposed to a steady flow. To gauge the general traffic flow, we counted the number of vehicles that passed a predetermined line perpendicular to the road in front of the measuring site. The layout of the intersection and measurement sites is shown in Fig. 1. Locations labeled A, B, and C, identify landmarks: the HKEPD roadside monitoring station, the sidewalk of the Pioneer Center shopping mall, and the entrance of the SKH Kei Wing Primary School, respectively. The equipment-to-roadside distances are 1 meter for *Site A*, 5 meters for *Site B*, and 6 meters for *Site C*. This distance is defined as the distance of the WCPC instrument inlet to the roadside curb. The particle counts of each site are most greatly affected by the road immediately adjacent: the north side of Lai Chi Kok road at *A*, Nathan Lane at *B*, and the south side of Lai Chi Kok road at *C*. Occasional showers took place between 15:00 and 16:50 hour; and continuous rainfall soon after 17:12 hour until the end of the sampling campaign at 17:51 hour.

RESULTS

Measurements were conducted on 30 July 2005 totaling approximately 4 hours, starting at 14:00 hrs. Fig. 1 shows vehicular flow around the intersection and the average number of vehicles per hour: 282 vehicles/hr north or south-bound on Nathan Lane; on Lai Chi Kok road, 150 vehicles/hr south-east bound and 126 vehicles/hr north-west bound. Numerous traffic lights and bus-stops keep the traffic flowing at low speeds.

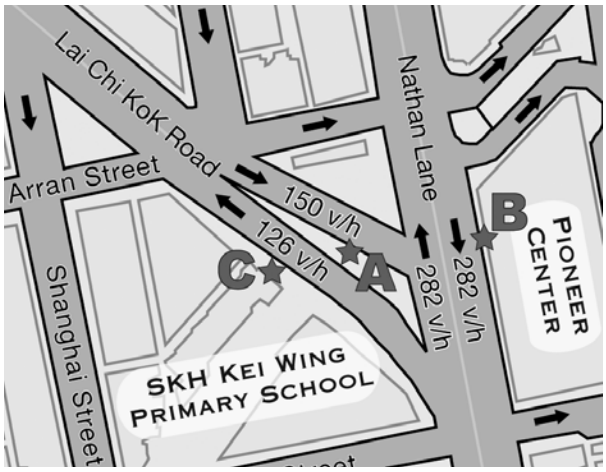
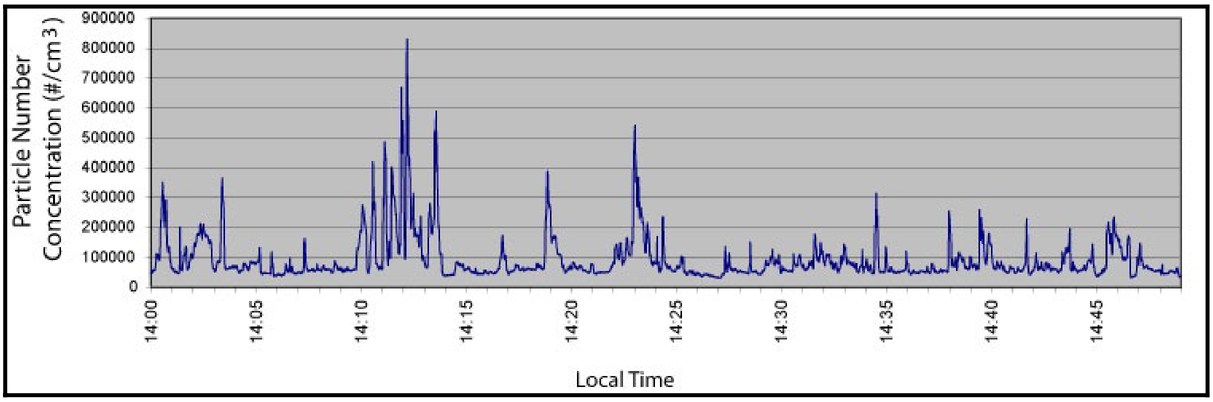


Fig. 1. Location A is located next to the HKEPD air quality monitoring station; location B at the Pioneer Center; and location C at the SKH Kei Wing Primary School. For each site, the road immediately adjacent is the main influence of the particle counts observed. Vehicular flow around the intersection and the average number of vehicles per hour are shown: 282 vehicles/hr north or south-bound on Nathan Lane, and on Lai Chi Kok road, 150 vehicles/hr south-east bound and 126 vehicles/hr north-west bound.

Double decked buses made up the majority of the vehicle types passing the intersection, followed by coach vehicles (less than 2% on Nathan Lane and 20% on Lai Chi Kok road). Less than 1% of vehicles entering the intersection were other types of vehicles such as

(a)



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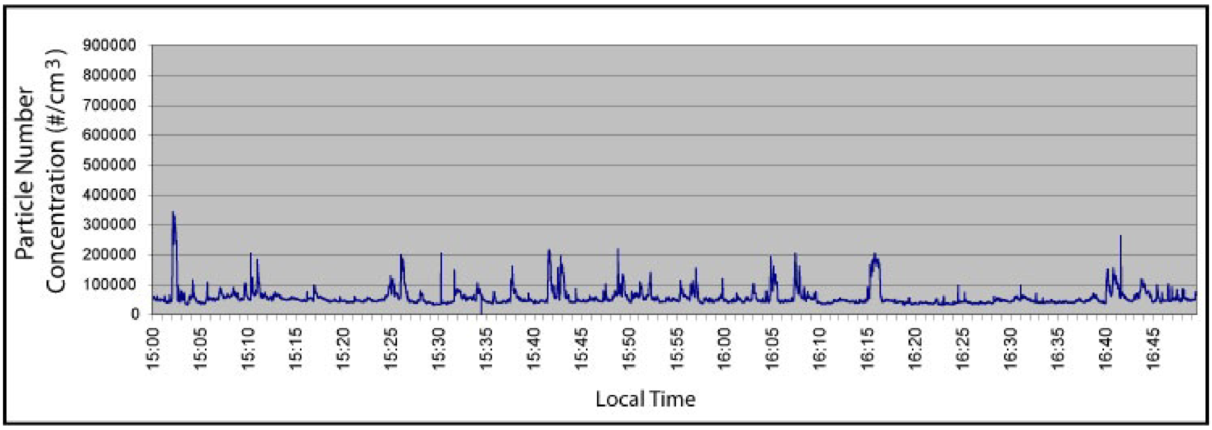
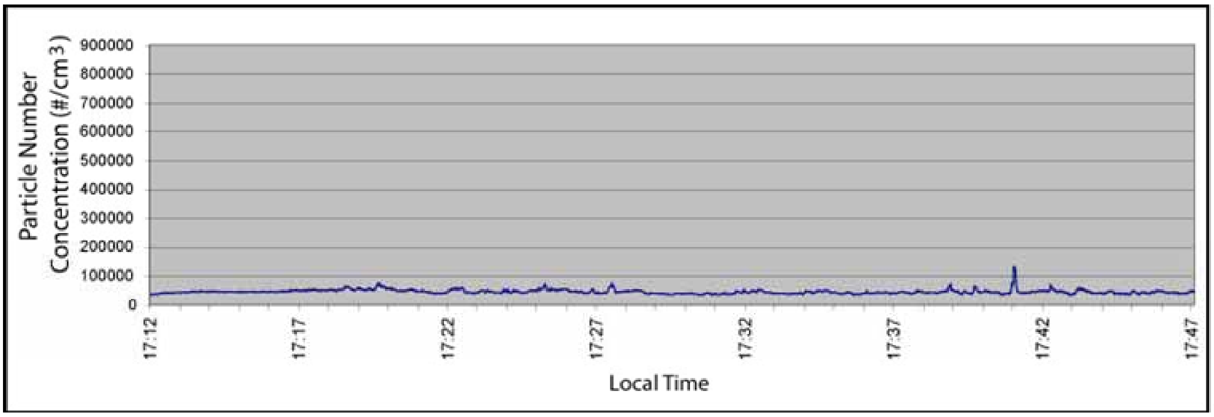


(c)



Figs. 2 a-c. Particle counts for the measurement intervals at each site, shown on the same scale. (a) The highest particle counts were observed at Site A with an average of 9.0×10^4 particle/cm^3. (b) An average particle count of 5.5×10^4 particle/cm^3 was measured at Site B by the Pioneer Center. (c) The particle counts at Site C was generally lower than Sites A and B at an average of 4.5×10^4 particle/cm^3.

Table 1. Average particle number concentrations and rain occurrence at each location.

Location and distance to road (m)	WCPC (particle/cm^3)	*Rain Occurrence*
A: HKEPD station, 1	89,705 ± 75546	None
B: Pioneer Center, 5	55,453 ± 29060	Occasional
C: Primary School, 6	45,088 ± 7358	Continuous

commercial trucks. Figs. 2(a-c) show one-second averaged particle number concentration measurements, respectively, for the entire intervals at *Sites A, B,* and *C*. Table 1 summarizes the average particle number concentrations for each of the sites along with the distance of the WCPC inlet probe from the curb. The highest peak 8.26×10^5 particle/cm^3 (Fig. 2(a)) occurred at 14:12:12 hour at *Site A,* collocated with the HKEPD station. At this site, the observed particle count averaged 9.0×10^4 particle/cm^3 during the sampling period (Table 1).

An average particle count of 5.5×10^4 particle/cm^3 was measured at Site B by the Pioneer Shopping Center (Fig. 2(b)), and were generally lower in front of the SKH Kei Wing Primary School (*Site C*) averaging 4.5×10^4 particle/cm^3 (Fig. 2(c)). In Figs. 3 a-b, the darkly shaded portions represent periods of red light and lightly shaded portions refer to periods of green light. When traffic patterns are superimposed on the particle count vs. time data (Fig. 3(a-b)), we clearly see that the peaks coincide with changes of traffic lights at site A. The ability of the WCPC to take data at a 1-second time resolution was integral to the ability to clearly view these peaks.

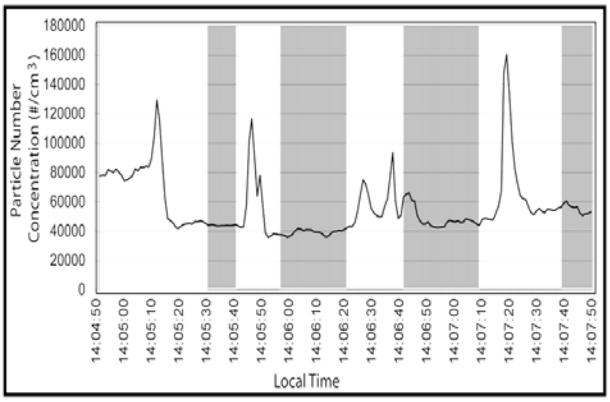
DISCUSSION

As expected from the high volumes and types of vehicles at any given moment, the peaks for the particle number counts show a diversity of forms and shapes. Incomplete mixing and complex plume dispersion patterns present a situation with many variables to consider. Expanded examples of peaks can be seen in Figs. 3(a-b) for measurements taken at site A. Many of the observed spikes of particle counts are small and typically last for a short period of time (10 to 45 seconds). Often, these spikes quickly ascend to a maxima of 1.6×10^4 particle/cm^3 before descending rapidly (Fig. 3(a)). The observed patterns regularly follow green lights; the peaks are clearly discernable from baseline count measurements.

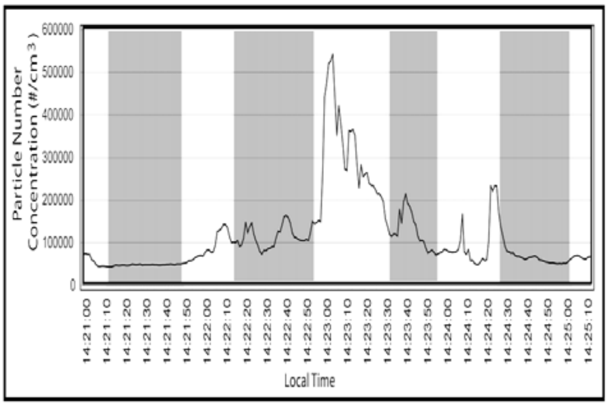
In contrast to the small spikes observed in Fig 3(a), larger peaks with high and prolonged particle counts dominate the distribution plots taken some 20 minutes later, as shown in Fig. 3(b). A sharp rise in particle count occurs approximately 3 seconds after the traffic light changes to green, as a result of vehicle acceleration.

Six seconds later the particle count plateaus at 5.4×10^5 particle/cm^3, after which it descends slowly over the next 35 seconds until the start of the red light period.

(a)



(b)



Figs. 3 a-b. Examples of typical peaks from Site A. (a) an expanded example of particulate matter emitted at the intersection during light-duty vehicle acceleration. (b) expanded particle counts of a gross emitter acceleration. Dark shaded time periods represent a red-light period for the light affecting the lane adjacent to the measurement site, and light shaded time periods denote a green-light period. The highest particle count in (a) is 1.6×10^5 particle/cm^3 and the highest count for (b) is 5.4×10^5 particle/cm^3.

These result shows that sudden acceleration of vehicles quickly emits a large number of particles. These peaks are characterized by very high particle counts and are front-heavy before trailing to lower counts. These large counts are likely to be linked to "gross emitter" heavy-duty vehicles. Imhof *et al*. (2005) reported that emissions corresponding to heavy duty vehicles were on average 10-30 times higher than light duty vehicles, the counts for the largest peaks in this study are easily 40 times greater than the highest lower peaks. This is not surprising, given that up to 10 heavy duty vehicles may accelerate from the intersection at the same time.

Zhu *et al*. (2002a) documented an exponential decay for total particle number concentrations with increasing distance from traffic, suggesting that atmospheric dilution, diffusion to surfaces, coagulation, and evaporation are the processes leading to decreases in the particle number concentration in the 10 nm diameter size range. After emission, particles experience coagulation from collision during Brownian motion (Hinds, 1999). This effect is increased for smaller particles which have larger diffusion coefficients. Thermal coagulation experienced by particle emissions reduces the particle number concentration and shifts the size distribution to larger sizes (Hinds, 1999). The rate of particle number decay is reflected in characteristic tailing or sharp decreases in number concentration peaks such as can be seen in Figs. 3(a-b). Clearly, atmospheric dilution and coagulation may contribute to the observed behavior of ultrafine particle counts during the Mong Kok campaign.

At the intersection, high vehicle density and overall stop-and-go traffic characterize Hong Kong rush hour. Vehicle counts show that the majority of traffic was comprised of double-decked buses, and other vehicle types only made up less than 2% of traffic for Nathan Lane and about 20% for Lai Chi Kok road. The plots of sample data count, superimposed with the pattern of the traffic lights (Figs. 3 a-b) show that spikes of particle counts occur mostly during the green light, in the wake of moving traffic in the lanes next to the measuring site. For *Site A*, the average PM count during the totaled green-light periods is generally higher (~9.4×10^4 particle/cm^3) compared to the average counts during red-light periods (~7.8×10^4 particle/cm^3), whereas the total average is 9.0×10^4 particle/cm^3. Such patterns are consistent with previous findings that vehicle acceleration is associated with increased particle emissions (Maricq *et al.*, 1999a, b; Imhof *et al.*, 2005). Due to variations in the general flow of traffic, the lag time between the peaks and the light change is somewhat variable and peaks do not always fall neatly into 'stop' and 'go' periods. Some of the traffic phenomena that may contribute to lag times include traffic jams, vehicles not following traffic laws, as well as periods with no vehicles at all. However, the general trend shows that high points of vehicular particle counts occur during the green light— while pedestrians are waiting for the light to change. On the other hand, many idling vehicles do not show such high particle counts.

CONCLUSIONS

Atmospheric dilution, increased distance from exhaust pipes, and time contribute to rapidly decreasing particle counts in the ultrafine and nanoparticle range after emission. The average particle number concentration around the intersection was 6.2×10^4 particle/cm^3. An order of 10^5 particles/cm^3 is often associated with acceleration of a heavy duty vehicle. High particle counts occur when vehicles accelerate. With a busy public transportation system, the large pedestrian population is vulnerable to exposure of toxic particulate matter. While these results are preliminary, they clearly suggest that reducing congestion would contribute greatly to improved air quality in this area, therefore diminishing pedestrian exposure to toxic UF particles.

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