



In-Cabin Commuter Exposure to Ultrafine Particles on Commuter Roads in and around Hong Kong's Tseung Kwan O Tunnel

Jason A. Kaminsky¹, Emily A.L.M. Gaskin², Masanori Matsuda³, Antonio H. Miguel^{4*}

¹ Graduate School of Business, Interdisciplinary Program in Environment and Resources, Yang and Yamzaki Environment and Energy Building-4210, 473 Via Ortega, Stanford University, Stanford, CA 94305

² National Oceanic and Atmospheric Administration, Fagatele Bay National Marine Sanctuary, Executive Office Building, Utulei, Pago Pago, American Samoa, 96799

³ Toyota Motor Corporation, Operation Department Vehicle Logistics Division, 4-7-1. Meieki Nakamura-ku, Nagoya, 450-8711 Japan

⁴ Haagen-Smit Laboratory, California Air Resources Board, 9528 Telstar Ave., El Monte, Ca, USA 91731

ABSTRACT

Over half a million cars pass through Hong Kong's tunnels every day. Commuters, taxi drivers, and other drivers who pass through these tunnels may be exposed to high levels of particulate matter and toxic gases present in the air. There is limited data on in-cabin exposure to pollutants, especially while the vehicle is driving through a tunnel under different cabin ventilation conditions. This study reports in-cabin measurements of fine particles (FP, $dp < 2.5 \mu\text{m}$) -- which includes nanoparticles and ultrafine particles (UFP, $dp < 100 \text{ nm}$) -- in a 1998 Nissan Sunny EX passenger car while driving through Hong Kong's Tseung Kwan O Tunnel. The vehicle tested did not contain a particle filtration system or an activated carbon filter, and was fueled with unleaded gasoline. The measurements were taken using a water-based condensation particle counter (WCPC) under different conditions consistent with driver behavior. The particle count readings were generally highest with the windows closed and air conditioning on. On average, these readings were more than three times higher than readings with the windows closed and the air conditioning off, and 68% higher than readings with the windows open and the air conditioning off. In-cabin particle concentrations inside the tunnel were up to twenty-one times higher than in-cabin particle concentrations outside the tunnel under comparable traffic conditions. The highest in-cabin particle count concentration reading, 1.94 million particles/cm³, was taken with the windows closed and air conditioning on while the test car was passing a double-decker diesel bus.

Keywords: In-cabin commuter exposure; Water-based particle counter; Hong Kong; Tseung Kwan O Tunnel; Roadway measurements; Ultrafine particles; Nano-particles.

INTRODUCTION

Everyday hundreds of thousands of drivers in Hong Kong are exposed to high levels of particulate matter in the atmosphere. Poor air quality is the result of regional and local conditions. Industry and power plants in the Pearl River Delta, southern China and the Hong Kong SAR emit particulate matter into the atmosphere. Low lying mountain ranges and high-rise buildings restrict air flow and increase particle number concentration. The air pollution problem is exacerbated by the large numbers of vehicles that drive on Hong Kong's roads and freeways. There are 271 vehicles per kilometer of road in Hong Kong compared to 33 in the United States (Louie, 2005). An estimated 30% of Hong Kong's vehicles operate with diesel fuel. Although the Hong Kong SAR government announced plans in 1999 to convert 6,000 buses to liquefied petroleum gas (LPG) and require heavy diesel vehicles to be fitted with diesel catalysts, buses and trucks continue to be the main contributors of diesel fuel emissions (Lam, 2004). Particulate matter is likely to become even more concentrated in tunnels where poor ventilation inhibits dispersion of air pollutants.

Frequent exposure to the type of airborne particulate matter

found in Hong Kong has been shown to have negative health effects. Ultrafine (UF, $dp < 100 \text{ nm}$) and nanoparticles are highly toxic, not only because of their small size and ability to localize in subcellular mitochondria, but also as a result of large number concentrations and high organic carbon content, including polycyclic aromatic hydrocarbons and quinones (Li *et al.*, 2003; Li *et al.*, 2004). UF particles, which can enter the circulatory system when inhaled, have been shown to be toxic to animals (Nemmar *et al.*, 2002; Donaldson and Stone, 2003; Oberdörster *et al.*, 2004). Experiments on mammals and fish suggest that nanoparticles with $dp < 50 \text{ nm}$ and associated soluble metals can be transferred to the brain via the olfactory bulb which in high concentrations could have adverse affects (Oberdörster *et al.*, 2004).

To date, very limited information is available on human exposure to freshly emitted UFP while traveling on major roads and freeways, and tunnels. In a recent study Zhu *et al.* (2007) reported that in-cabin and outdoor particle size distributions are mostly bimodal in the 7.9-217 nm diameter size range, with the primary peak occurring at 10-30 nm and the secondary at 50-70 nm. Using a WCPC they reported that up to 85% of these particles may be removed by a factory-installed filter/activated carbon system when both vehicle's fan and recirculation were on.

Tsang *et al.* (2008) evaluated the exposure of pedestrians to vehicular emissions of UF particles while walking near several high volume pedestrian walkways, in areas of high vehicular traffic volume located in the urban mega city Mong Kok of Kowloon, Hong Kong. They reported that the highest particle

* Corresponding author. Tel.: 1-626-350-6521;
Fax: 1-626-575-6818
E-mail address: amiguel@arb.ca.gov

counts occurred when vehicles accelerate, after stopping at a signal light or a bus stop. Peak WCPC concentrations as high as 5.4×10^5 particle/cm³ were observed during acceleration of a heavy-duty diesel bus near a sidewalk.

We report a study of in-cabin measurements of ultrafine particles ($dp < 100\text{nm}$) taken in real-time with a WCPC in a 1998 Nissan Sunny EX passenger car while driving through Hong Kong's Tseung Kwan O Tunnel, under different combinations of open/closed windows and on/off air conditioning conditions.

METHODS

The Tseung Kwan O Tunnel is one of thirteen tunnels found in Hong Kong. The 900 meter tunnel connects Kwan Tong and Tseung Kwan O New Town (Fig. 1). In 2004 an estimated 67,700 cars, trucks and buses passed through the tunnel every day (Government of HKSAR). Many drivers, including commuters and taxi drivers, pass through the tunnel several times a day and are therefore more susceptible to the harmful effects of particulate matter than the general population.

In-cabin air quality refers to the levels of pollutants inside a car. In-cabin air quality was tested in the Tseung Kwan O Tunnel on July 12th, 2005 using a 1998 Nissan Sunny EX automatic transmission, fueled by unleaded petroleum, that did not contain a particle or activated carbon filter capable of efficiently removing UF particles (Zhu *et al.*, 2007). The exposure conditions tested reflected the conditions commonly experienced by drivers in Hong Kong. The three conditions included windows open with the ventilation system (air conditioning) off, windows closed with the air conditioning off, and windows closed with the air conditioning on. When the air conditioning was turned on it was set to level four, the highest setting available. All four windows were open or closed where indicated. Although this may not necessarily be the representative for all vehicles, the study was designed to show what was expected to be extreme scenarios with the windows open. A total of eight return trips were made through the tunnel for a total of sixteen passes.

A laminar flow, water-based condensation particle counter (WCPC, TSI Model 3785, Saint Paul, MN) was used to measure particle number concentration (#/cm³). The WCPC measures concentrations of particles in the 5 nm-3 μm d_p size range. Power was supplied by a deep cycle 12 V battery and inverter to run the WCPC and a laptop. A full description of the WCPC design and calibration is found elsewhere (Hering and Stolzenburg 2005a; Hering *et al.*, 2005b). Briefly, the WCPC enlarges small particles to a size that is large enough to be detected optically, using a water-based condensation technique. Particles pass through a cooled saturator and then a heated condenser, where particles serve as condensation sites.

Measurements were taken in near real-time by equipment held down by bungee cords to the middle of the back seat of the car. The WCPC provides a maximum reading of 10^7 particles per cubic centimeter and should not be used in environments that exceed 40°C. Readings were taken at 20 second intervals recording an average of the data collected every second during that interval. Each pass through the tunnel lasted just over one minute when traveling at 40-60 km/h and on average three readings were taken for each pass through the tunnel. Simultaneous measurements of concentrations of carbon monoxide (CO), temperature and relative humidity (RH) were taken at one minute intervals on a continuous basis by a Q-Trak IAQ Monitor (Model 8550, TSI Inc., Saint Paul, MN). Both the WCPC and the Q-Trak monitor were factory-calibrated before use in this study.

RESULTS AND DISCUSSION

The results indicate that driver exposure in the tunnel is greater than anywhere else along the various locations in the commute route (Fig. 2). Fig. 3 illustrates the particle concentration data collected by the WCPC. The maximum recorded in-cabin particle concentration was 1.94 million particles/cm³ when passing a diesel double-decker bus; the minimum recorded particle concentration was 10,775 particles/cm³ at a gas station near Hong

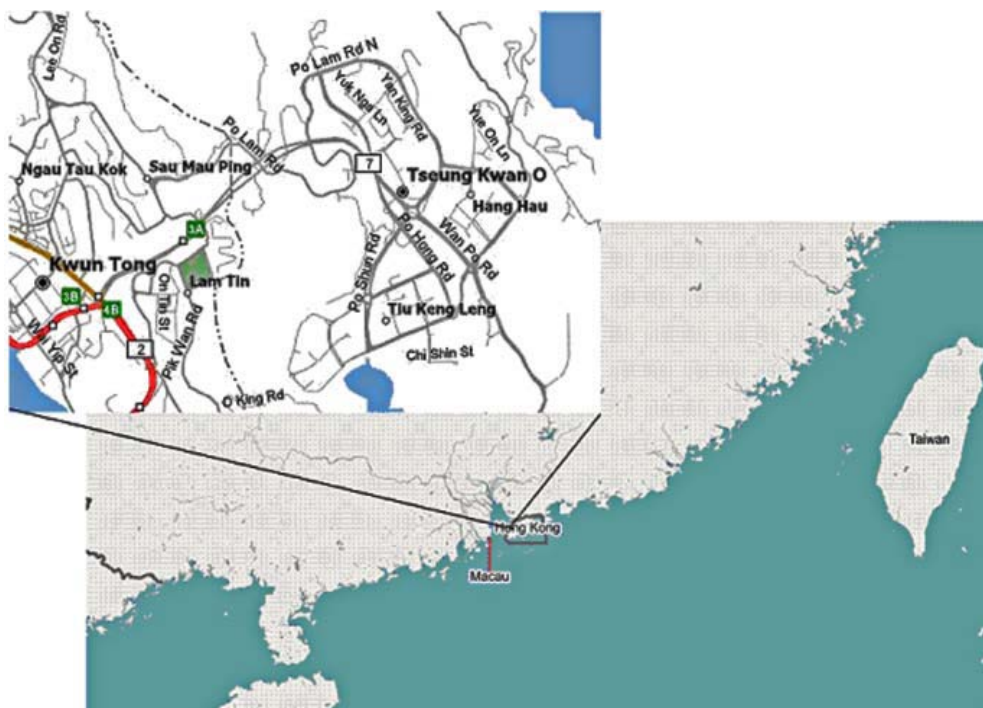


Fig. 1. A map of the route, highlighting Hong Kong's location in Southeast Asia. The tunnel is between the points marked "7" and "3A".

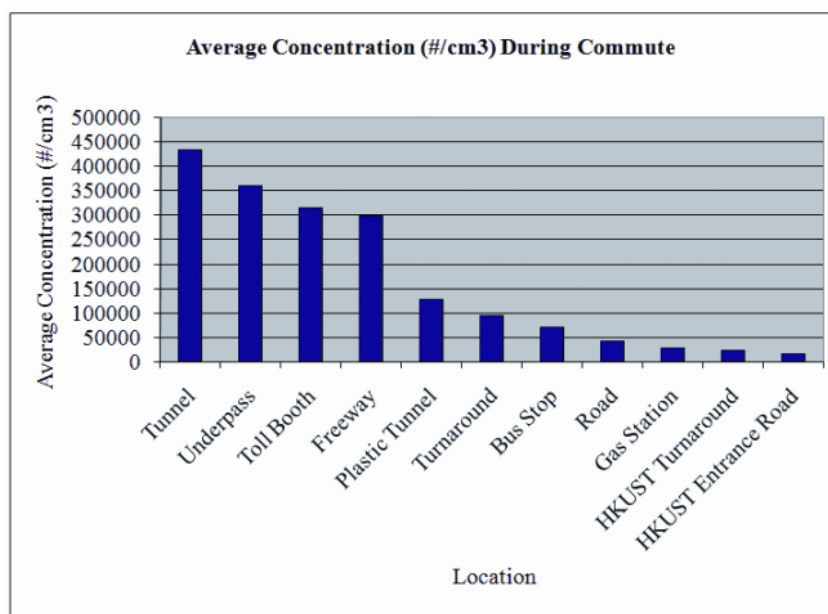


Fig. 2. Average particle exposure (#/cm³) at different points during the drive.

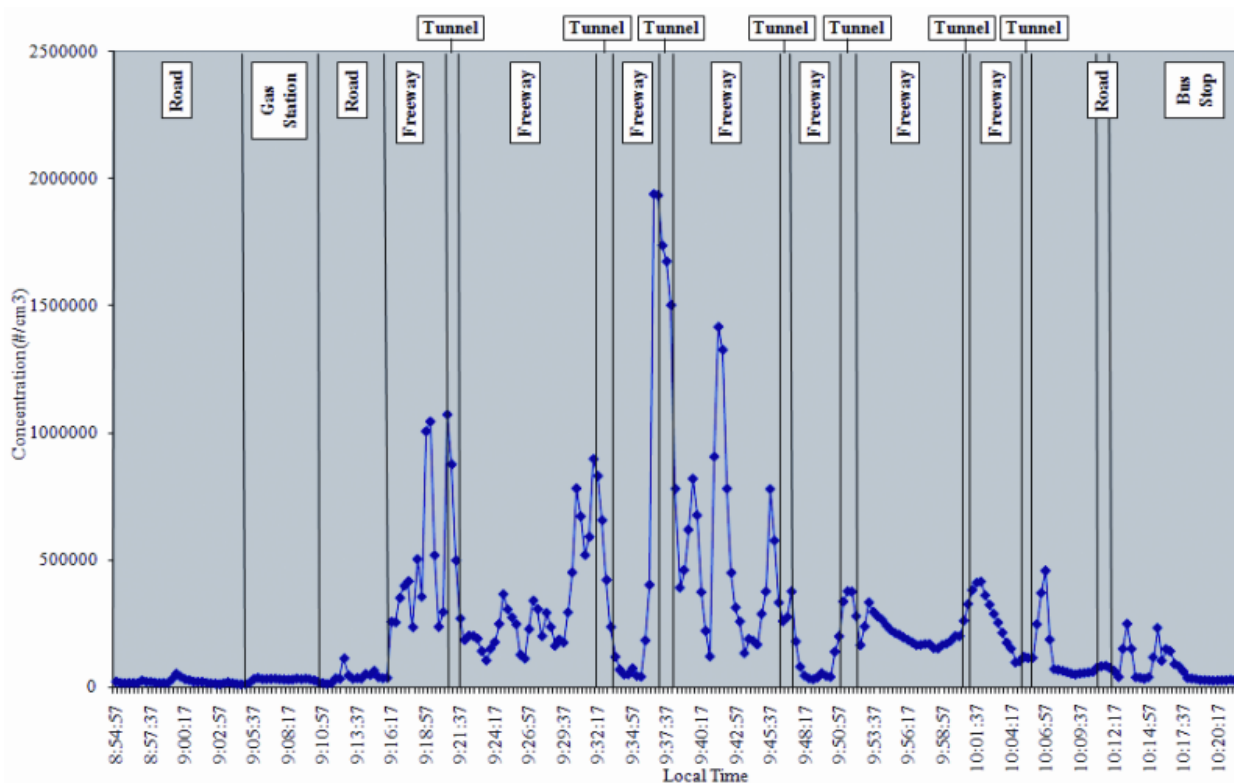


Fig. 3. 20 second averaged readings of the entire trip. Tunnel readings are indicated by arrows, with ventilation system status indicated at the top.

Kong University of Science and Technology. In both situations the windows and doors were closed and the air conditioning was on. The in-cabin particle number concentration increased sharply when inside the tunnel (Fig. 3). Outside the tunnel in light traffic with the windows open, readings were typically less than 100,000 particles/cm³, with a minimum reading of 28,650 particles/cm³. Inside the tunnel in light traffic with the windows open, particle number concentrations were between 201,495 and 590,850

particles/cm³. Similarly, outside the tunnel in light traffic with the air conditioning on, measurements were less than 100,000 particles/cm³, with a minimum reading of 41,020 particles/cm³. Inside the tunnel in light traffic with the air conditioning on, particle number concentrations were between 375,850 and 896,850 particles/cm³. Readings inside the tunnel with the air conditioning on were at times more than twenty-one times higher than those taken outside the tunnel in comparable conditions.

The status of the vehicle ventilation system is an important factor in determining in-cabin particle count concentrations. In general, the highest particle concentrations were recorded with the windows closed and the air conditioning on. For example, in the tunnel with air conditioning on, while passing a diesel truck, there were 1.07×10^6 particles/cm³ in-cabin. By contrast, lower particle number concentrations were recorded when the windows were open or windows were closed with the air conditioning off. In this case readings near large diesel vehicles were 520,850 particles/cm³ and 409,150 particles/cm³ respectively. This point is further emphasized by looking at the average particle count concentrations inside of the tunnel (Table 1). The readings with the air conditioning on were on average three times higher than the readings with the windows closed and the air conditioning off, and 68% higher than the readings with the windows open. As previously noted, exhaust from nearby vehicles dramatically affected in-cabin air quality. Within 30-40 seconds of passing or driving near a diesel truck or bus with visible black smoke emissions, in-vehicle particle counts exceeded 1 million particles/cm³ on four separate occasions.

The toll booth on the south end of the Tseung Kwan O Tunnel requires most vehicles to stop. The CO readings were frequently higher while ten or more seconds were spent waiting in line to pay. At the tollbooth cars and trucks were traveling at slow speeds, with high outside temperature and air conditioning on, which leads to higher than normal CO emissions (Singh *et al.*, 2001). There was a maximum CO reading of 10.1 ppm, with instantaneous concentrations probably reaching much higher levels. US-EPA puts the 1-hour CO limit at 35 ppm and the 8-hour limit at 9 ppm; Hong Kong Air Quality Objectives for 1-hour CO are 30,000 µg/m³ and for 8-hour CO are 10,000 µg/m³ (26.8 ppm and 8.93 ppm, respectively, at 33°C). While the concentrations of CO at the tollbooth do not pose much concern to the commuter, they could be potentially harmful to the tollbooth worker, who is exposed to these high CO levels for many hours at a time. It is interesting to note that there is only a

weak positive correlation between particle number and CO concentrations ($r = 0.239$). There were times with a high particle number concentration to CO concentration ratio, consistent with secondary particle formation or gas-to-particle formation after the combustion exhaust leaves vehicle tail pipes. CO peaks were observed when following or passing diesel vehicles, including a double-decker bus.

There are a couple of variables that should be acknowledged since they may have affected the readings taken by the WCPC. For one, there were four passengers in the car while the tests were being taken. Humans inside a vehicle influence UFP concentrations. The human respiratory system removes UFPs, thereby reducing their concentrations. On the other hand, particle generation by the human presence may increase the number concentration.

This effect may not be important inside well ventilated vehicles with significant influx of outside air (Zhu, 2007). Another condition that may have influenced our data is the duration and timing of the readings. All of the readings were taken over a three hour period and all but one of the readings with the air conditioning on and two of the readings with the windows closed and the air conditioning off were taken between 9:19 am and 9:52 am. The rest of the readings with the windows closed and the air conditioning off and all of the readings with the windows open were taken between 12:00 and 12:52 pm. It is possible that variations in particle concentration in the tunnel between these time periods influenced our readings. However for the purpose of this study, we believe it is safe to assume tunnel air conditions to be very similar throughout the day.

CONCLUSIONS

The water-based CPC 3785 indicates that particle number concentration is higher in the Tseung Kwan O Tunnel than on surrounding roads. In-cabin particle number concentration was highest when the air conditioning was on and lowest when the

Table 1. In-cabin values of particle number concentration with varying ventilation conditions, while inside the tunnel. Averages for the pass are found in the last column, while the averages and standard deviation of each ventilation condition are at the bottom. Largest readings are found with the windows closed and air conditioning on.

Pass	Windows Closed			Windows Closed			Windows Open			Pass Avg.
	AC on			AC off						
	#1	#2	#3	#1	#2	#3	#1	#2	#3	
1	295050	1.07×10^6	876100							747650
2	591050	896850	830550							772816
3	1.93×10^6	1.74×10^6	1.67×10^6							1782000
4	258950	275250								267100
5	336200	376950	375500							362883
6				199550	260400	326350				262100
7				113950						113950
8							500200	500350		500275
9							383450	446400	539800	456550
10				228850	323050					275950
11							201495	520300	590850	437548
12							528650	565750		547200
13				50390	194300					122345
14				409150	345300					377225
15							282500	520850		401675
16	418050	561200								489625
Average		781843			245129			465049		
SD		557281			110501			118336		

air conditioning was off and the windows were closed. Despite the potential discomfort caused by an increase in temperature, a taxi driver or frequent commuter through the Tseung Kwan O tunnel would be advised to temporarily turn off his or her air conditioning while passing through a tunnel, if the vehicle does not contain a factory-installed particle/gas filter/activated carbon filter system. Additionally, drivers should avoid passing diesel trucks and buses since particle number concentration increases exponentially as one approaches its exhaust pipe. Alternatively, vehicles with factory-installed particle/gas filter/activated carbon filter system can decrease concentration of particles ranging in diameter from 15-600nm by 85-98% (Miguel *et al.*, 2003; Miguel *et al.*, 2005).

A more permanent solution is to decrease on-road pollution levels. The Hong Kong Environmental Protection Department has recommended several alternatives to decrease vehicle pollution, including converting diesel taxis to low petroleum gas, fitting particulate traps to all diesel vehicles and using ultra-low sulfur diesel (Louie, 2005). An overview on air pollution control in Hong Kong, available in the EPD website, illustrates a number control measures that have been implemented to date.

However, until pollution levels in the Tseung Kwan O tunnel improve, drivers should do what they can to minimize their in-cabin exposure to air pollutants while driving through tunnels.

ACKNOWLEDGEMENTS

We would like to thank Mr. Hing S. Tsui from the Center for Coastal and Atmospheric Research (CCAR) at HKUST for his help with the equipment, Dr. Jian Zhen Yu for the use of her car and Mr. Eric Wan for graciously driving the vehicle during the experiment. Our thanks also go to Quant Technologies LLC (Blaine, MN) for allowing us the use a WCPC sold under the TSI brand, and Guyline (Asia) Ltd. for facilitated receipt of the instrument in Hong Kong. Finally, we acknowledge the University of California, Los Angeles-Hong Kong University of Science and Technology joint summer program for making this study possible.

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Received for review, September 19, 2008
Accepted, March 9, 2009