

FINAL REPORT

Assessing and Reducing Taxi Drivers' Exposure to Ultrafine Particles

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LIST OF TERMS AND ABBREVIATIONS

Abbreviations	Descriptions
1-OHP	1-hydroxypyrene
AER	Air Exchange Rate
ARB	California Air Resources Board
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATCM	Airborne Toxic Control Measure
BC	Black Carbon
CO	Carbon Monoxide
CPC	Condensation Particle Counters
HECA	High Efficiency Cabin Air
HVAC	Heating, Ventilating, and Air-Conditioning
I/O Ratio	In-cabin to On-roadway Concentration Ratios
MDA	Malondialdehyde
OA	Outdoor Air
OEM	Original Equipment Manufacturer
PM	Particulate Matter
PM ₁₀	Particulate Matter with Aerodynamic Diameter Equal to or Less than 10 µm
PM _{2.5}	Particulate Matter with Aerodynamic Diameter Equal to or Less than 2.5 µm
RC	Recirculation
UFP	Ultrafine Particle

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ABSTRACT

Taxi drivers are expected to have high occupational exposure to traffic-emitted air pollutants because they spend long working-hours on freeways and local streets where concentrations of air pollutants such as ultrafine particles (UFPs) are high. In this study, we focused on two specific aims: (1) to identify the major factors that impact the taxi drivers' occupational exposure to UFPs and (2) to develop a cost-effective strategy to mitigate taxi drivers' occupational exposure to UFPs.

We recruited 22 taxi drivers in the Greater Los Angeles area in California in this study. We worked with each of them to collect air pollutant data, environmental factors (i.e. temperature, humidity, and noise level), and health indicators (i.e. ambulant blood pressure and heart rate). For each driver and his/her taxi cab, tests were conducted on four consecutive days. On each test day, the driver drove 6 hours in the Greater Los Angeles area as he or she would typically do. One field technician rode along in the taxi cab operating and maintaining all the sampling instruments. For the first two days, the original equipped manufacturer (OEM) cabin air filter was used in the taxi cab, to represent the drivers' actual working conditions. For the last two days, a custom-made High Efficiency Cabin Air (HECA) filter was used to replace the OEM cabin air filter, to test the effectiveness of HECA filter in reducing taxi drivers' occupational exposure to UFPs. In addition to the two proposed specific aims, we also (1) calculated the air exchange rates (AERs) in taxi cabin by using CO₂ as tracer gas, (2) collected and analyzed taxi drivers' urine samples twice a day to explore the biomarkers of UFP exposures, and (3) explored how the exposure to air pollutants impact taxi drivers' ambulatory blood pressure.

On average, taxi drivers in the Greater Los Angeles area work 11.9 ± 2.3 hours a day, and 6.1 ± 0.8 days a week. The on-road data collected from this study, showed UFP concentration ranges from 10^5 to 5×10^5 particles/cm³. Data showed that the on-road UFP concentrations were affected by the road type (freeways or local streets), however, driving speeds didn't affect the UFP levels significantly. The AERs were generally higher in taxi cabs compared with private passenger vehicles. The UFP in-cabin to on-roadway (I/O) ratios in taxi cabs were not significantly different between freeways and local streets, but affected by the interventions (window positions and HECA filter availabilities) significantly. Using HECA filter can significantly reduce both the UFP concentrations and UFP I/O ratios in taxi cabs. The reduction was more obvious when the drivers kept the windows closed. Results from the urinary biomarker analysis showed 1- and 2-NAP, 1-PYR and 9-FLU levels in the taxi driver group were significantly higher than the general population.

SECTION 1

SIGNIFICANT FINDINGS

For Aim 1, we found that Ford Crown Victoria (31.6%), and Toyota Prius (26.6%) were the most popular taxi vehicle models. The survey also showed that on average, the surveyed subjects have worked as taxi drivers for 9.8 (mean) \pm 8.3 (SD) years. They work 11.9 \pm 2.3 hours a day and 6.1 \pm 0.8 days a week. On average, the surveyed taxi cabs have higher mileages than passenger vehicles of the same car age.

The on-road data collected from this study, showed UFP concentration ranges from 10^5 to 5×10^5 particles/cm³. Moderate linear correlations were detected between on-road UFP concentrations and total traffic/heavy duty diesel vehicle (HDDV) with R²s of 0.24 and 0.31, respectively. Data showed that the on-road UFP concentrations were affected by the road type (freeways or local streets), however, driving speeds didn't affect the UFP levels significantly.

For Aim 2, simultaneous on-road and in-cabin sampling results showed UFP in-cabin levels followed its on-road trends when the vehicle ventilation was under outside air (OA) mode or the car windows were open. When the taxi windows were closed, ventilation was set to OA mode at the medium fan level, with HECA filter in use, the in-cabin UFP concentrations were still following the on-road pattern, but the levels were apparently lower than the on-road UFP concentrations.

The UFP in-cabin to on-roadway (I/O) ratios in taxi cabs were not significantly different between freeways and local streets, but affected by the interventions (window positions and HECA filter availabilities) significantly. The speed didn't show apparent correlation with taxi I/O ratios either. The taxi vehicle mileages were moderately or highly correlated to their average I/O ratios with a R² of 0.56. The taxi vehicle make model was an important factor that affecting its I/O ratios.

Using the HECA filter can significantly reduce both the UFP concentrations and UFP I/O ratios in taxi cabs. The reduction would be more obvious if the drivers keep the windows closed.

In addition to the proposed two aims, we also found the air exchange rates (AERs) were generally high in taxi cabs, ranging from several to hundreds of air exchange per hour. The AERs were affected by vehicle models. Crown Victoria had the highest overall AERs among all five tested taxi models. AERs were higher when driving on freeways than driving on local streets. In addition, the urinary biomarker analysis results showed 1- and 2-NAP, 1-PYR and 9-FLU levels in the taxi driver group were significantly higher than the general population. The possible factors affecting the 1-PYR levels could be driver age, years as driver, shift time, sampling time, creatinine levels, UPF levels and PM_{2.5} levels, based on a longitudinal model.

TRANSLATION OF FINDINGS

This study collected close to 500 working hours of data from 22 taxi drivers. The survey data showed that taxi drivers in the Greater Los Angeles area work much longer than the standard 40 hours per week work time. Their work environments have much higher concentrations of UFPs, compared with other work places. Therefore they have higher risks of occupational exposures to UFPs and other traffic related air pollutants (TRAP).

The High Efficiency Cabin Air (HECA) filter has been demonstrated to reduce the taxi drivers' occupational exposure to UFPs. Therefore it is recommended to replace the taxi cabs' OEM filter with HECA filter to protect the taxi drivers from UFP exposure.

This study also found that, with HECA filter installed, keeping cab windows closed as much as possible can further reduce the taxi drivers' exposure to UFP. Therefore it is suggested that taxi drivers should keep their windows closed during their work hours, to reduce their occupational exposure to UFPs.

It was found that driving on local streets lead to lower UFP exposures since the local streets usually have lower UFP concentrations and the measured UFP I/O ratios were also lower.

OUTCOMES AND IMPACTS

Since exposure to UFPs and other traffic-related air pollutants (TRAP) can cause adverse health effects to taxi drivers, the findings of this project can help them reduce their UFP exposures in the workspace, and thus reduce their occupational risks.

The fact that some vehicle models had significant higher overall AERs can be potentially helpful to form new policy which promotes the usage of certain vehicle models as taxi cabs in the future. By using vehicles with less air leakage, the taxi drivers' occupational exposures to UFP and TRAP could be reduced.

The findings on urinary biomarkers and heart rate variability of taxi drivers provided insights on how the UFPs affect taxi drivers' health and can potentially draw more attention to this research area. Further research in this area could lead to further understanding about the occupational health not only of taxi drivers but also occupations with similar high exposures to UFPs.

SECTION 2

1. BACKGROUND

Epidemiological studies have reported deleterious health effects of traffic-related air pollutant (TRAP), (Pope, Dockery et al. 1995) that contain particulate matter (PM) of different sizes such as PM_{2.5} (aerodynamic diameter $\leq 2.5 \mu\text{m}$), black carbon (BC) and ultrafine particles (UFPs, diameter $\leq 100 \text{ nm}$). Exposures to high levels of UFPs, BC, and PM_{2.5} have been associated with pulmonary and cardiovascular health risks (Oberdorster 2001; Gilmour, Ziesenis et al. 2004; Weichenthal, Godri-Pollitt et al. 2013). UFPs have been shown to induce oxidative stress, mitochondria damage, and acute pulmonary inflammation (Li, Sioutas et al. 2003; Strak, Janssen et al. 2012; Kroll, Gietl et al. 2013).

Previous studies have shown that traffic emissions significantly increase in-cabin concentrations of UFP, BC, and PM_{2.5} on local arterial roadways and freeways (Hitchins, Morawska et al. 2000; Tainio, Tuomisto et al. 2005; Morawska, Ristovski et al. 2008). The on-road UFP concentration typically ranges from 10,000 to 500,000 particles/cm³ (Zhu, Eiguren-Fernandez et al. 2007), which is one or two orders of magnitude higher than a typical ambient level in an urban environment. Occupational exposure to TRAPs, although has not been regulated and monitored, are of concern for certain groups of workers, such as traffic police, drivers, and street vendors.

A total of over 4000 taxi drivers are working 7-12 hours a day and six days a week in Los Angeles (LA DOT 2010). Given their prolonged work hours and the heavily trafficked Los Angeles roadways, taxi drivers working in this area are exposed to high levels of TRAPs. Their in-vehicle percent of daily UFP exposure is likely to be much larger than people in other occupations. The vehicle in-cabin PM levels are usually lower than the on-road levels because of the different mechanisms of particle loss (Zhu, Eiguren-Fernandez et al. 2007). Research studies conducted on regular passenger vehicles showed in-vehicle to on-roadway (I/O) ratio of particulate pollutants ranges from 0-0.4 when the vehicle was under in-cabin recirculation mode, from 0.6 to 1.0 under outside air (OA) mode (Hudda and Fruin 2013). However, there is an information gap on the I/O ratio ranges of the taxi cabs. These I/O ratios are essential for estimating taxi drivers' occupational exposure to PM.

There are many factors affecting drivers' exposure to in-cabin TRAPs. These factors include on-roadway particle concentrations, air exchange rates (AER), particle penetration factors, deposition rate inside vehicles, and vehicle cabin filter efficiencies (Xu and Zhu 2009). On-roadway PM levels, affected by emissions from surrounding vehicles, are by far the most important factor determining the in-cabin exposure. Besides on-roadway pollutant levels, AER and vehicle ventilation setting are also important factors affecting in-cabin UFP levels. A wide range of vehicle AER, from 1.6 h⁻¹ to 71 h⁻¹, has been reported depending on vehicle speed, window position, ventilation system, and AC settings (Fletcher and Saunders 1994; Ott and Siegmann 2006). With closed windows and passive ventilation, the AERs were linearly related to the vehicle speeds over a range from 15 to 72 mph. Opening a single window by 7.6 cm increased the AER by 8–16 times. AER values at higher fan settings under outside air (OA) mode have been reported to be 73% higher than at lowest fan setting (Knibbs, de Dear et al. 2009; Knibbs, de Dear et al. 2009). AERs could be an order of magnitude higher under OA mode than under RC mode and were primarily driven by blower fan speed not vehicle speed (Fruin, Hudda et al. 2011).

Taxi vehicles are used more frequently than private passenger vehicles, meaning higher mileage should be expected on taxi vehicle, given a passenger vehicle of the same car age. This suggested that the taxi vehicles can be expected to be more torn and worn, and therefore leakier than regular passenger vehicles. It is suggestive to the idea that the AER in taxi vehicles could be substantially higher than those in regular passenger vehicles.

Previously we have developed a theoretical model to investigate the particle in-cabin to on-roadway (I/O) concentration ratios for passenger vehicles (Xu and Zhu 2009). We found the most significant determinants of I/O ratios were ventilation conditions and filtration efficiency of cabin filters (Xu and Zhu 2009). Under three different ventilation conditions, (1) Fan off-RC off, (2) Fan on-RC off, and (3) Fan on-RC on, the modeled UFP I/O ratios were found to be 0.40, 0.25 and 0.10, respectively (Xu and Zhu 2009). These results agree well with experimental data collected inside passenger vehicles (Zhu, Eiguren-Fernandez et al. 2007). Although recirculating cabin air decreases in-cabin UFP levels, a rapid build-up of in-cabin CO₂ levels will occur under this ventilation condition because there is a minimal air exchange between the in-cabin and the outside. In some cases, CO₂ from exhaled breath of passengers can build up within a few minutes and exceed Cal-OSHA exposure limits of 5000 ppm for eight hours a day in cars when vents are set to RC on and windows are closed (Zhu, Eiguren-Fernandez et al. 2007). Although CO₂ is non-toxic at the atmospheric concentration, exposure to high CO₂ concentration was associated with a variety of health effect, such as dry eyes, sore throat and nose, wheeze and other respiratory illnesses (Apte, Fisk et al. 2000). In sensitive population, the health effect of high CO₂ exposure is more severe. Patients with bipolar disorder were more anxious and breathed more deeply and rapidly when exposed to high CO₂ levels (MacKinnon, Craighead et al. 2007). In comparison to 600 ppm CO₂, human exposed to CO₂ level of 1000 ppm had decreased decision-making performances in four categories (i.e., basic activity, applied activity, information usage, and breath of approach). Exposures to 2500 ppm CO₂ significantly reduced the decision-making performances in four more categories (i.e., focused activity, task orientation, initiative, and basic strategy) (Satish, Mendell et al. 2012). To overcome the CO₂ build up issue, sufficient air exchange between in-cabin and outside is needed. Under “vent open – OA mode” condition, improving cabin filter efficiency is a promising low-cost strategy to reduce PM_{2.5} and UFP exposures inside taxi cabs.

Tremendous progress has been made to reduce vehicular emissions by tightening emission standards. However, the potential to further reduce taxi drivers' exposure to TRAPs by reducing the proportion of on-roadway pollutants penetrating into and remaining inside vehicles is largely overlooked. Currently, most of the modern passenger vehicles are equipped with cabin air filters; however, the overall protection against UFPs is limited to 40–60% under OA mode and the filtration efficiency varies as a function of particle size (Qi, Stanley et al. 2008; Xu, Liu et al. 2011). In this study we examined the effectiveness of the newly developed high efficiency cabin (HECA) filter for taxi vehicles on roadways.

Polycyclic aromatic hydrocarbons (PAHs), a category of hydrocarbons, are ubiquitous in the air, water, and soil, due to incomplete combustion of fossil fuels (Lee, Wang et al. 1995). In the atmosphere, PAHs distributes between the gaseous and particulate phases. PAH species with lower molecular weights (2-4 aromatic rings) were mainly found in the gaseous phase, whereas PAHs with five or more rings are predominantly in aerosol phase depending on the volatility of the species (Baek, Field et al. 1991). The PAHs with higher number of aromatic rings have the higher toxicological interest (Vione, Barra et al. 2004).

PAHs pose risks to human health as many of the individual PAHs are cytotoxic and mutagenic, for example, benzo-a-pyrene, benz-a-anthracene, and benzo-β-fluoranthene, have been

identified as carcinogens, mutagens, and teratogens (Xue and Warshawsky 2005). Sixteen PAH compounds are listed as hazardous air pollutants by US Environment Protection Agency. The US Occupational Safety and Health Administration (OSHA) has set up an 8-hour permissible exposure limit (PEL) of 0.2 mg/m³ of total PAHs. The major urban environmental emission source of PAHs in the ambient air is usually the road traffic, although PAHs can be generated from any other incomplete burning process such as cooking, wildfire, and industrial emissions (Harrison, Smith et al. 1996; Marr, Dzepina et al. 2006). A study showed that the concentration of a total of 27 PAHs in the air sampled from a city street was 8.3 times higher than that in the air sampled from rural area, and was 5.3 times higher than that in the air sampled from a building rooftop in the center of Tainan city, Taiwan (Lee, Wang et al. 1995). These findings suggested that certain occupational groups that spend a significant portion of their working time on or near the street and freeways, such as taxi and bus drivers, mail and pizza delivery workers, will have higher occupational exposure to PAHs than other occupational groups do.

Occupational PAH exposure studies have been conducted for truck drivers and post office employees that shows bus drivers are more exposed to PAH than mail carriers. Mail carriers who worked outdoors had higher urinary concentration of 1-OHP than those working indoors (Hansen, Wallin et al. 2004). However, so far very limited effort has been made for taxi drivers. In this study, we studied 22 active LA taxi drivers and expect to observe higher PAHs exposure levels, and that the tested mitigation methods will be effectively in reducing their occupational exposures.

Many of the PAH metabolites have been detected in human urine samples. A widely used indicator of PAH exposure level is urine concentration of 1-OHP corrected by creatinine concentration (Jongeneelen 2001). 1-OHP is commonly used due to its relatively high urinary concentration and low detection limit. Concentrations of 1-OHP in different samples become comparable after corrected by the creatinine concentration in each sample, because creatinine is usually produced by the human body muscle at a constant rate. The assumption is that urinary creatinine excretion is constant across and within individuals so it can be used to control for urine flow rate.

In this study, we collected urine samples before and after each 6 hour monitored work shift. Urinary malondialdehyde (MDA) was measured as the oxidative stress marker. Nine different urinary monohydroxylated PAH metabolites were analyzed, including 1- and 2-hydroxynaphthol (1- and 2-NAP); 1-, 2-, 3- hydroxyphenanthrene (1-, 2- and 3-PHE); 2-, 3-, 9-hydroxyfluorene (2-, 3-, and 9-FLU); and 1-hydroxypyrene (1-PYR). Fourteen UCLA researchers served as a control group and the urine samples were collected and analyzed following the same procedure that administered to the taxi driver group. Since the taxi drivers were monitored under four different conditions (before and after work shift; with and without the exposure mitigation method), we will be able to answer these important questions: Is the taxi drivers' occupational exposure to PAHs higher than the control group exposure? Does their elevated occupational PM and PAH exposure affect the oxidative stress levels?

2. SPECIFIC AIMS

Mass concentrations of regulated PM₁₀ and PM_{2.5} have dropped under established regulations, but PM related cardiorespiratory diseases continue to rise (Pope and Dockery 2006). Strong evidence has demonstrated that unregulated UFPs are more toxic per unit mass than already regulated larger particles; however, the current lack of quantitative UFP exposure and risk

assessment precludes establishing number based standards (Ferin, Oberdorster et al. 1990; Oberdorster, Ferin et al. 1990; Frampton, Stewart et al. 2006). In an urban environment, vehicular emissions usually constitute the most significant source of UFPs and the time spent in traffic and living close to roadways have been linked to adverse respiratory and cardiovascular health effects (Peters, von Klot et al. 2004; Panasevich, Leander et al. 2013). On roadways, in-cabin UFPs have been shown to be 10 times higher than average ambient levels and contribute to approximately 50% of total daily UFP exposure among LA commuters (Zhu, Eiguren-Fernandez et al. 2007; Fruin, Westerdahl et al. 2008). While increasing efforts have been made to assess UFP exposure and health effects in the general population, no comparable studies have been conducted in the occupational settings. Transportation workers are expected to be exposed to high levels UFPs because of their close proximity to the source and prolonged exposure time. There is a critical data and knowledge gap on transportation workers exposure to UFPs at work and even less knowledge about the influencing factors leading to high exposure. Lack of such knowledge is an important problem because until reliable data and knowledge regarding exposure causes and correlates are available, associated health effects studies will remain limited, and appropriate UFP regulations and mitigation policies cannot be set.

Our long term goal is to reduce occupational diseases attributable to UFP exposure at workplaces. The objective of this study was to develop UFP exposure assessment instrument and explore novel low cost UFP exposure mitigation strategies for taxi drivers. The central hypothesis is that (1) vehicle characteristics and driving conditions will explain a significant portion of the total variability of taxi drivers' exposure to UFPs; and (2) replacing commercially installed vehicle cabin air filters with HECA filters will significantly reduce taxi drivers' exposure to UFPs.

We tested the central hypothesis by pursuing the following two specific aims:

1. Developed an exposure assessment instrument by identifying major factors that influence UFP concentrations inside taxi cabins. We found on-road UFP concentrations and the in-cabin to on-road (I/O) concentration ratios was two essential factors that determine in-cabin exposure to vehicle emitted UFPs. Based on the data we collected inside the taxi cabins, roadway conditions (traffic density and driving speed) correlated with on-road UFP concentrations, and taxi vehicle conditions and characteristics (window position and ventilation settings, age, size) predicted I/O ratios.
2. Developed low-cost exposure mitigation strategies to reduce taxi drivers' exposure to UFPs. Previous studies showed a large range of filtration efficiency (i.e., 20-80%) was observed for different commercial cabin filters. In this study, replacing commercially installed vehicle cabin filters with HECA filters will significantly reduce taxi drivers' exposure to UFPs.

Beside the originally proposed two aims, we also (1) calculated the air exchange rates (AERs) in taxi cabin by using CO₂ as tracer gas, (2) collected and analyzed taxi drivers' urine samples twice a day to explore the biomarkers of UFP exposures, and (3) explored how the exposure to air pollutants impact taxi drivers' ambulatory blood pressure.

3. METHODOLOGY

3.1 Recruitment of Taxi Drivers

A recruitment campaign was conducted at the Los Angeles Airport (LAX) taxi holding lot from February 11th to 15th, 2013. A questionnaire which included 10 questions to collect taxi drivers' basic information such as age, race, smoking history, car model and car age etc. was designed and used in this recruitment campaign. It can be assumed that every registered taxi driver in Los Angeles have been exposed to this recruitment campaign, since they will work on the airport every fifth day and the recruitment campaign lasted for 5 consecutive days. The chance of them not showing up in the taxi holding lot on their 'airport day' is rare because they can usually earn 2 -3 times more than they do on a regular 'none airport day'. A total of 2449 survey forms were handed out and 316 effective survey forms were collected back. Out of these 316 taxi drivers, only the 121 driver who indicated they never smoked cigarettes were used as the sampling pool, because smoking cigarettes will lead to huge dose of PM exposure which might outweigh the drivers' occupational exposure to TRAPs. In order to ensure that the sampled car models have a similar distribution with that of all the taxi vehicles in Los Angeles, stratified random sampling was conducted based on car models and 22 taxi drivers were selected to participate in the field measurement.

The study design and experimental protocol were submitted to UCLA Institutional Review Board (IRB) in early 2012 for review and were approved on June 20, 2012 (IRB#A12-000845). All research personnel involved in the recruitment had completed CITI training courses.

3.2 Selection of Testing Taxis

Twenty two taxi drivers and their taxis were selected to investigate their in-cabin UFP exposure and reductions resulting from the application of the HECA filters. As listed in Table 1, to ensure the sampled taxi drivers/vehicles are representative, these 22 taxi drivers were randomly selected from the 121 never smoked taxi drivers stratified by their taxi make/model, and drivers' age based on the information of the 316 responders of our recruitment survey at LAX Taxi Holding Lot.

It should be noted, the size of the OEM filter is not proportional to the cabin volume. The OEM filters across different vehicle models were similar in size (approximately 10 x 10 inches), but slightly different in shapes. We were able to locate filter housings for all of the originally proposed vehicle models except for the Ford Crown Victoria. Therefore, a portable vehicle cabin high efficiency particulate air (HEPA) purifier was used to test Ford Crown Victoria taxis. These five cab models were selected among popular taxi models in California. According to the California Department of Transportation, in southern California, small cabin vehicles (passenger cars and pickups) account for 63% of the total fleet and large cabin vehicles (SUVs and vans) of different models and types from different manufacturers and countries of origin account for 37%. However, taxi vehicles are supposed to be larger than regular passenger vehicles on average because of their commercial uses.

To reflect the potential variability that can result from vehicle aging, tested taxis were selected from different model years ranging from 2005 to 2012. The accumulated mileage of the vehicles ranged from 56,409 to 385,191 miles. All test models were equipped with an in-use OEM filter except for the Ford Crown Victoria, and the cabin air filter housing was found behind glove boxes.

Table 1 A summary of the tested taxi models and specifications

Vehicle Type	Maker	Model	Number	Made Year	Average Mileage (SD) (mile)	Cabin Volume ¹ (m ³)
Hatchback	Toyota	Prius	10	2005-2012	114,000 (39,000)	3.28
Sedan	Ford	Crown Victoria	5	2005-2008	277,000 (93,000)	3.78
	Toyota	Camry	3	2009-2012	118,000 (46,000)	3.34
	Chevy	Uplander	1	2005	269,000	8.11
Minivan	Dodge	Grand Caravan	3	2007-2012	176,000 (82,000)	8.75

3.3 Development of High-Efficiency Cabin Air (HECA) Filters

Since high efficiency filters are not currently marketed for passenger vehicles, two types of automotive HECA filters (noted here as HECA A and HECA B) were developed in collaboration with an industrial partner. These two types of HECA filters has been proven to have particle removal efficiency of 85 - 95% in another study conducted in our research group (Lee and Zhu 2014) where the details of characteristics and manufacturing specifications can be found. In this study, we used only HECA A filters to replace the applicable OEM filters in the taxi cabs.

3.4 Driving Conditions and Testing Route Selections

Each of the selected 22 taxi vehicles were tested under four different driving conditions on four consecutive test days. The four test conditions were summarized in Table 2. On the first test day, taxi driver controlled vehicle window positions and the taxi vehicle cabin filter setting remained unchanged from the manufacturer conditions (OEM filter or no filter for Ford Crown Victoria). On the second test day, the taxi windows were kept closed, and the taxi vehicle cabin filter setting remained unchanged from the manufacturer conditions (OEM filter or no filter for Ford Crown Victoria). On the third test day, taxi windows were closed, and the OEM cabin filter was replaced with the HECA filter. On the fourth test day, the taxi driver controlled window position, and the OEM cabin filter was replaced with HECA filter.

Table 2. Summary of Taxi Vehicle Test Conditions

Day ID	Window Position	Ventilation Setting	Cabin Filter
1	Open or Closed	Any	None or OEM Filter
2	Closed	OA* Mode, mid fan level	None or OEM Filter
3	Closed	OA* Mode, mid fan level	HECA or Air Purifier
4	Open or Closed	Any	HECA or Air Purifier

*OA=Outside Air

On each test day, the driver drove approximately 6 hour in the Greater Los Angeles area as he would typically do in his everyday work. One field technician rode along in the taxi cab operating all the sampling instruments. The starting time of each test was based on the driver's availability and kept consistent for the four consecutive test days for the same driver in order to minimize the differences in traffic and meteorological conditions among each day. No actual fares were picked up during the tests and the drivers' time and efforts were compensated by the research fund. Each driver was allowed to take breaks as he would during his typical work hours. The

time and location of each break were recorded by hand and confirmed by a GPS unit (Qstarz GPS BT-1000XT, Taipei, Taiwan).

The driving routes were not specifically planned for each driver. Instead, on the first test day for each driver/taxi, he was asked to drive from the start location (University of California Los Angeles) to the area where he usually works and repeat what he did in the previous day. The same route was used as much as possible for the following three test days, to minimize the differences among each test day for individual drivers. In total, measurements were conducted on 83 different days from April 2013 to November 2013. Five test days were lost due to two Caravan drivers only partially completed their four-day tests. The total mileage driven by the 22 taxi drivers in this study was approximately 11,000 kilometers and the total hours of field measurement was approximately 500 hours. The testing routes included local city streets, arterial roads and freeways in Los Angeles air basin Figure 1.

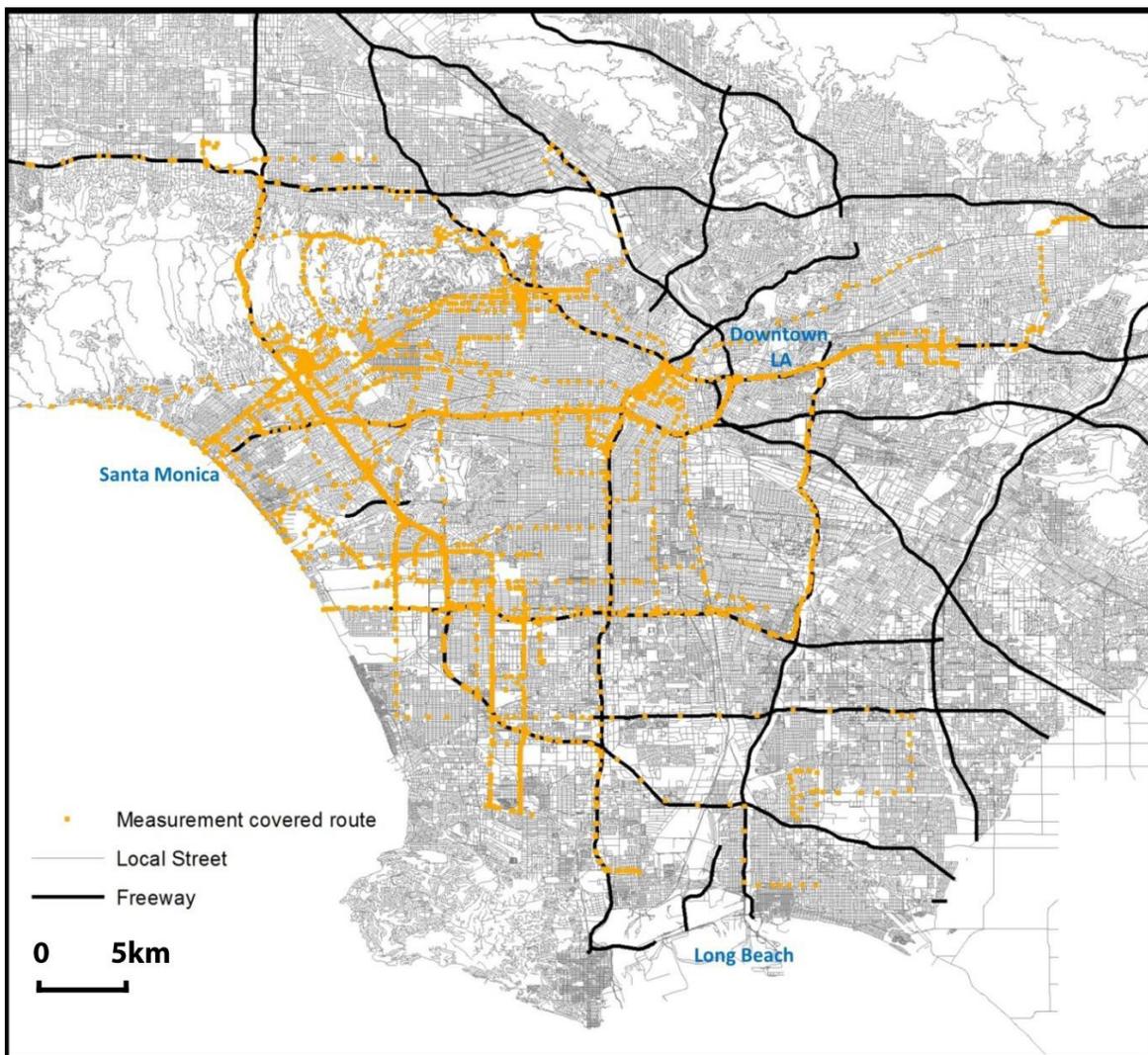


Figure 1. Test routes for taxis. Both local roadway and freeway were selected for the on-road tests.

3.5 Field Measurements

During the field measurements, the in-cabin and on-road concentrations were concurrently monitored by two sets of portable real time sampling instruments for UFPs, PM_{2.5}, and CO₂. While both sets of instruments were located inside the taxi cabin, one set monitored near the breathing zone of the taxi driver inside the taxi cabin, and the other set sampled the air outside of the vehicle at the same location across different test vehicles as seen in Figure 2. The on-roadway aerosols were sampled through a 3 mm (id) isokinetic probes mounted on the car window. The window gaps were sealed with painter's tape (or masking tape) similar to a previous study (Zhu, Eiguren-Fernandez et al. 2007). Similar probes were used for in-cabin air sampling to compensate any diffusion loss in the sampling lines. In addition to measuring particulate pollutants, the AERs in taxi cabins were calculated based on the mass balance of CO₂. The details of this AER measurement and calculation are provided in Section 3.7.

Air sampling instruments used for the taxi tests were summarized in Table 3. Two portable condensation particle counters (CPCs) were deployed to measure the in-cabin and on-road (Model 3007, TSI Inc., St. Paul, MN) UFP concentrations. Similarly, two DustTrak (Model 8520, TSI Inc., St. Paul, MN) and two Q-trak monitors (Model 8554, TSI Inc., St. Paul, MN) simultaneously measured the in-cabin and on-road concentrations of PM_{2.5} and CO₂. Although CO data were also collected by the Q-trak, the data were invalid even after several lab calibrations. This is likely because the CO levels were too low and below the instrument detection limit. For all test vehicles, when the windows were closed, the air conditioning was on with setting fan level to the medium level. All of the instruments were calibrated prior to their deployment for field sampling and set to a logging interval of 1 s.

Table 3 List of Sampling Collection Instruments

Parameter	Instrument	Make and Model
UFP (10nm-1.0µm diameter) Number Concentration	Portable CPC	TSI Inc. 3007
PM _{2.5} (w/ PM 2.5µm impactor) Mass Concentration	Dust-Trak	TSI Inc. 8520
Temperature, Relative Humidity, CO, & CO ₂	Q-Trak	TSI Inc. 8554
Speed and location (Latitude, Longitude and Altitude)	Global Positioning System (GPS)	QSTARZ, Travel Recorder BT-Q1000x

Each vehicle model was evaluated with two occupants (taxi driver and technician) for driving scenarios. The same sets of instruments with the same configuration were used to monitor in-cabin and on-road air quality for all tested taxis.

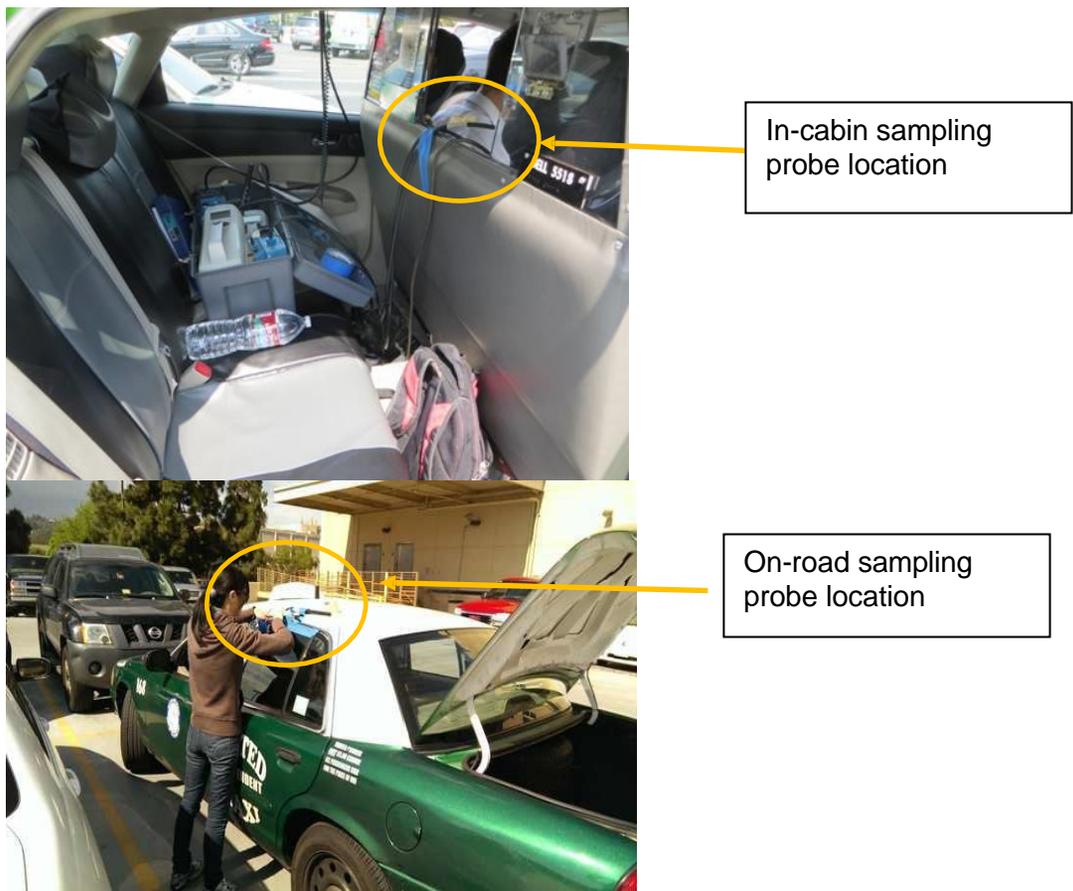


Figure 2 Pictures of in-cabin and on-road sampling probe locations in a tested taxi cab. Air samples were collected at the same location in the 22 taxi vehicles selected in this study.

3.6 Acquisition of Data and Quality Assurance

Each pair of instruments was collocated before and after the field sampling for data quality assurance. Good correlations with little bias of the collected data were observed. The collocation data for UFP and $PM_{2.5}$ were well correlated with R^2 of 0.98 and 0.96, respectively. UFP and $PM_{2.5}$ collocated data were within 5% of each other and R^2 was higher than 0.95.

The instruments measured $PM_{2.5}$ (Model 8520, TSI Inc. Shoreview, MN) could be affected by ambient conditions (e.g., temperature and relative humidity) during the day of testing although the collocated data show a good correlation ($R^2 > 0.95$) and little bias ($< 5\%$) for both in-cabin and on-road $PM_{2.5}$ measurements.

The instruments used in this study provided high time resolution data with one-second sampling interval. The collected data were thoroughly checked and unrealistic data points, caused by instrument malfunction, were removed before data analysis. Then, one-second raw instrument data were averaged to five-minute to minimize unnecessary data fluctuations. The five-minute averaged data were used for data analyses and data presentation in this study.

3.7 Measurements beyond the Proposed Two Aims

3.7.1 Air exchange rates measurements in taxi cabin

The AER measurements were conducted by using CO₂ as a tracer gas, a method which has been proven to be relatively easy yet accurate in regular passenger vehicles (Fruin, Hudda et al. 2011). Two Q-Trak Indoor Air Quality Monitors (TSI Inc., MN USA) were used to measure simultaneously the in-cabin and on-road CO₂ concentrations. One Q-Trak had its probe placed outside, usually attached to the top of taxi cab (Figure 2), to measure the on-road CO₂ concentrations. The other Q-Trak was placed in taxi cab and the probe was fixed at the center of the cabin, between taxi driver and the field technician who sat on the back seat (Figure 2). Previous studies have shown that the well-mixed condition of in-cabin CO₂ can be assumed (Fruin, Hudda et al. 2011; Hudda, Kostenidou et al. 2011; Lee and Zhu 2014). Both Q-Traks were reading and recording CO₂ concentrations at one second time resolution. Later on these CO₂ concentrations were averaged by one minute to reduce data fluctuation. The two Q-Traks were calibrated using gas standards in the lab and then collocated with each other at different CO₂ levels. The collocation test showed that the readings from the two units correlated well ($R^2 > 0.95$), although not exactly the same. Thus, the readings from the in-cabin unit were corrected against the on-road unit, by using the linear correlation equation obtained from the collocation test, assuming the on-road unit was the 'gold standard'. An AER model based on CO₂ mass balance in the taxi cabin was built, as shown in Equation (1).

$$V \frac{dC_i}{dt} = E + Q(C_o - C_i) \quad \text{(Equation 1)}$$

where V is the volume of cabin in m³, which is reported by the vehicle manufacturer, C_{in} , and C_o are the in-cabin and on-road CO₂ concentrations in mg m⁻³, respectively, E is the emission rate of CO₂ in the cabin in mg min⁻¹, and Q is the air flow rate from outside into the cabin in m³ min⁻¹. By rearranging Equation (1) and using its discrete form, Equation (2) was obtained and used to calculate the AER at time t .

$$\frac{C_{in}(t+\Delta t) - C_{in}(t-\Delta t)}{2\Delta t} = AER(t) \times [C_o(t) - C_i(t)] + E/V \quad \text{(Equation 2)}$$

where AER is a function of time and equals to Q/V in min⁻¹. During the data processing, all data were averaged over one minute, to reduce the noise from the instruments. Therefore the Δt in Equation (2) was one minute and all the AERs calculated in this study were one-minute averaged values and converted in unit of h⁻¹.

The value of in-cabin CO₂ emission, E , was estimated based on the number of people in the vehicles. During all the experiments, there were two people inside the vehicle during driving: the driver and the field technician. It was assumed that the driver and the technician, at the activity level between sedentary to lightly active, generates 0.68 L CO₂ per minute (McArdle, Katch et al. 2010), which equals to one adult generating 900 grams of CO₂ in a day. The authors are aware of the uncertainty in this respiration CO₂ production rate. Due to the fact that all the tested drivers are adults with BMI of 26.7 ± 4.5 kg m⁻², the uncertainty of E was estimated to be $\pm 16\%$. Since the calculated AERs were linearly related to the E , the uncertainty in calculated AERs was approximately $\pm 20\%$, taking other uncertainties, such as the $\pm 10\%$ accuracy of Q-Trak readings, into account.

During test, everything was kept as similar to the driver's everyday working conditions as possible and the drivers had control over all the vehicle operations such as opening/closing windows, turning air conditioning (AC) on or off, setting ventilation to recirculation or outdoor air

mode. The AERs measured thus best represent the AERs experienced by Los Angeles taxi drivers during their everyday job.

The time and location of each break were recorded by hand and confirmed by a GPS unit (Qstarz GPS BT-1000XT, Taipei, Taiwan). Data collected during the breaks were not used to calculate AERs. The measured GPS coordinates and AERs were matched by the instrument time stamps during data processing. Then a piece of computer code was used to check if the taxi was on freeways or on local streets, by using an identification algorithm based on the GPS coordinates and the Los Angeles GIS database, which was downloaded from the Los Angeles County GIS Data Portal (<http://egis3.lacounty.gov/dataportal>). Student t-test was used to make inferences on whether AERs are higher while driving on freeways compared to that while driving on local streets.

A Generalized Estimating Equation (GEE) model was developed to analyze the importance of different factors that can potentially impact AERs. Many factors, such as driving speed, car age, car mileage, and the driver themselves all have great potential to impact the AER in a taxi cabin during driving (Knibbs, De Dear et al. 2009; Fruin, Hudda et al. 2011). As previously found (Fruin, Hudda et al. 2011) and confirmed in this study, the AERs measured repeatedly on the same vehicle were correlated. For example, an old Ford Crown Victoria will consistently have higher AERs than a new Toyota Prius across all driving speed, given same window position and ventilation settings. Therefore GEE model was selected because it is a widely used statistical model for data collected from repeated measurements on the same statistical unit, in this case, the taxi cab. A series of models were built in R software by using the GEE package. All the aforementioned potential influencing factors were used as input variables and their individual significance in the models was calculated. The model with the smallest Quasi Akaike Information Criterion (QIC) was chosen as the final model. Since the distribution of measured AERs was highly right-skewed, natural log transformation was performed on AERs before fitting the model.

3.7.2 Urine biomarker analysis

In addition to studying the taxi drivers' exposure to UFPs during their work time, urine samples were collected before and after each work shifts during the four day field tests. Exploratory investigation was conducted on the urinary biomarkers of taxi driver PAH exposure and quantifying exposure induced oxidative stress levels. Nine different urinary monohydroxylated PAH metabolites were analyzed, including 1- and 2-hydroxynaphthol (1- and 2-NAP); 1-, 2-, 3-hydroxyphenanthrene (1-, 2- and 3-PHE); 2-, 3-, 9-hydroxyfluorene (2-, 3-, and 9-FLU); and 1-hydroxypyrene (1-PYR). Fourteen UCLA researchers served as a control group and their urine samples (n=122) were also collected during the same field tests timeframe, and analyzed following the same procedure administered to the taxi driver group.

Urine samples were collected from the 22 "never smoked" taxi drivers' for 4 consecutive work days at the same time when their real time PM exposure levels were measured and logged. The monitored taxi drivers filled out a food consumption log before each monitored work shift on food and drink consumption during the past 24 hours before the urine samples were collected. Both pre- and post-work shift urine samples were collected on the 4 monitored days. The control group urine samples were collected and analyzed following the same procedure that administered to the taxi driver group. Since the taxi driver urine samples were collected at the same time as the exposure monitoring, the taxi driver urine results reflected four different testing conditions (before and after work shift; with and without the exposure mitigation method).

All urine samples were stored in a -20° C freezer before further chemical analysis. Urinary monohydroxylated PAH metabolites were analyzed by the California Department of Public Health laboratory. The urinary MDA levels were analyzed at Peking University College of Environmental Science and Engineering. The method for analyzing MDA in urine samples was modified from a published method that used an HPLC system with fluorescent detection. Briefly, urine sample was added to a mixture of phosphoric acid thiobarbituric acid (TBA, 42 mM). A derivative reaction between MDA and TBA occurred and lasted for 1 hour at 80 °C in an oven. After the reaction, the solution with MDA-TBA derivatives was injected into the HPLC system with a fluorescence detector set to 532 nm for the excitation wavelength, and 553 nm for the emission wavelength. A Nova-Pak C,8 column (Waters, USA) was used along with a mobile phase that was composed of 40% methanol and 60% water containing 50 mM KH₂PO₄ (pH = 6.8) at a flow rate of 0.8ml/min. The detection limit, extraction recovery, and analytical precision of this method were 1.8 nM, 75.9%, and 2.2% (measured as relative standard deviation (RSD) from eight replicate injections), respectively. The individual urinary monohydroxylated PAH metabolite and MDA results were normalized with the same urine creatinine concentrations of each sample.

3.7.3 Blood pressure and heart rate variability measurements

The blood pressure (BP) and heart rate variability (HRV) of each taxi driver were also measured during the test. A wrist BP monitor (Omron HEM-670) was used to measure taxi drivers' BP at different time points: (1) during the test right after stopped driving, (2) during the test after taking at least 5 minutes rest after stopped driving, (3) during working outside the 6-hour test window, and (4) during the non-working hours. For the first two time points, the BP was measured by the taxi driver him/herself under supervision of the field technician. All the BP data were measured when the taxi driver was in the position of sitting. While for the latter two time points, the BP was measured by taxi driver alone. The blood pressure data measured on the first three occasions were categorized as 'working' and those measured during the non-working hours were categorized as 'Non-working'. Shapiro-test was used to first check the normality of BP data and t-test, when appropriate, was used to check if there is any difference in blood pressure when the drivers were at work and not at work.

A set of Heart Rate Monitoring Watch and chest strip (Polar, RS800CX model) was put on the taxi driver during the entire 4 test days to record their heart rate. The drivers were instructed to keep the watch and strip on as much as possible during their respective test for the whole 4 test days. Later on the heart rate data were analyzed and the 5-min averages of 11 different HRV indexes were calculated. The UFP, PM_{2.5}, Leq, CO₂, and RH data were synchronized with heart rate data and their 5-min averages were also calculated, in order to explore the impacts of these factors on the taxi drivers' HRV.

4. RESULTS AND DISCUSSION

4.1 Aim 1 Exposure Factor Identification

Aim 1 is to develop an exposure assessment instrument by identifying major factors that affect UFP concentrations inside taxi cabin. The objective of this aim is to monitor UFP and other traffic related air pollutant concentrations simultaneously inside and outside taxi cabins in real-time and relate measured UFP levels to vehicle characteristics and driving conditions to develop exposure models. The working hypothesis is that driving conditions (traffic volume and speed) correlates with on-roadway UFP concentrations, and taxi characteristics (age, size, window position, and ventilation/cabin filter settings) can predict UFP I/O ratios. With GPS based time-location data, these factors will allow us to build statistical models to estimate taxi driver UFP exposure levels at work.

4.1.1 Characteristics of Studied Population

Basic descriptive information about the taxi drivers were collected from the first recruitment forms handed out at LAX taxi holding lot. The information included the drivers' demographic information, age, height/weight, education, marital status, whether smoke, work out frequency, and health conditions such as heart conditions, hypertension, respiratory conditions and diabetes. The information was summarized in Table 4.

Table 4 Descriptive Statistics of the Studied Population

Category	Count (percentage of total)	Heart Condition (% of each Category)	Hypertension (% of each Category)	Respiratory Conditions (% of each Category)	Diabetes (% of each Category)
Age					
<25	5 (1.6)	0	0	0	0
25-35	43 (13.6)	2 (4.7)	4 (9.3)	1 (2.3)	2 (4.7)
36-45	65 (20.6)	0	7 (10.8)	1 (1.5)	2 (3.1)
46-55	94 (29.7)	9 (9.6)	21 (22.3)	10 (10.6)	14 (14.9)
>55	109 (34.5)	14 (12.8)	42 (38.5)	10 (9.2)	20 (18.3)
Total	316 (100)	25 (7.9)	74 (23.4)	22 (7.0)	38 (12.0)
BMI					
<18.5	6 (1.9)	0	1 (16.7)	0	1 (16.7)
18.5-25	84 (26.6)	6 (7.1)	10 (11.9)	3 (3.6)	8 (9.5)
25-30	152 (48.1)	10 (6.6)	33 (21.7)	10 (6.6)	13 (8.6)
>30	74 (23.4)	9 (12.2)	30 (40.5)	9 (12.2)	16 (21.6)
Total	316 (100)	25 (7.9)	74 (23.4)	22 (7.0)	38 (12.0)
Education					
Less than high school	13 (4.1)	2 (15.4)	5 (38.5)	1 (7.7)	4 (30.8)
Some high school	35 (11.1)	1 (2.9)	2 (5.7)	2 (5.7)	3 (8.6)
High school diploma or GED	55 (17.4)	4 (7.3)	11 (20.0)	3 (5.5)	4 (7.3)
Some college or associate's degree	81 (25.6)	7 (8.6)	16 (19.8)	5 (6.2)	8 (9.9)
Bachelor's degree	97 (30.7)	7 (7.2)	27 (27.8)	6 (6.2)	12 (12.4)
Some graduate school	8 (2.5)	1 (12.5)	1 (12.5)	1 (12.5)	2 (25.0)

Graduate degree (M.A., Ph.D. etc.)	27 (8.5)	3 (11.1)	12 (44.4)	4 (14.8)	5 (18.5)
Total	316 (100)	25 (7.9)	74 (23.4)	22 (7.0)	38 (12.0)
Ethnicity					
Black	79 (25.0)	3 (3.8)	17 (21.5)	2 (2.5)	8 (10.1)
Hispanic/Latino	21 (6.6)	1 (4.8)	4 (19.0)	3 (14.3)	3 (14.3)
White/Non-Hispanic	128 (40.5)	13 (10.2)	34 (26.6)	14 (10.9)	16 (12.5)
Asian	58 (18.4)	4 (3.1)	15 (25.9)	3 (5.2)	7 (12.1)
Native American	0				
Pacific Islander	0				
Other	30 (9.5)	4 (13.3)	4 (13.3)	0	4 (13.3)
Total	316 (100)	25 (5.7)	74 (21.8)	22 (4.4)	38 (12.0)
Marital Status					
Married/Living with partner	225 (71.2)	18 (8.0)	51 (22.7)	17 (7.6)	29 (12.9)
Divorced/Widowed	52 (16.5)	4 (7.7)	16 (30.8)	2 (3.8)	5 (9.6)
Never Married	39 (12.3)	3 (7.7)	7 (17.9)	3 (7.7)	4 (10.3)
Total	316 (100)	25 (5.7)	74 (21.8)	22 (4.4)	38 (12.0)
Smoke					
Never	127 (40.2)	7 (5.5)	21 (16.5)	7 (5.5)	11 (8.7)
Quit	96 (30.3)	9 (9.4)	30 (31.3)	9 (9.4)	12 (12.5)
Smoke 1 cig or less	10 (3.2)	2 (20.0)	2 (20.0)	2 (20.0)	1 (10.0)
Smoke 2-10 cig	44 (13.9)	3 (6.8)	6 (13.6)	1 (2.3)	6 (13.6)
Smoke 0.5-1 pack	18 (5.7)	1 (5.6)	8 (44.4)	2 (11.1)	3 (16.7)
Smoke more than 1 pack	21 (6.6)	3 (14.3)	7 (33.3)	1 (4.8)	5 (23.8)
Total	316 (100)	25 (5.7)	74 (21.8)	22 (4.4)	38 (12.0)
Work out frequency					
0 days/week	133 (42.1)	10 (7.5)	33 (24.8)	9 (6.8)	15 (11.3)
1 day/week	76 (24.0)	3 (3.9)	14 (18.4)	4 (5.3)	9 (11.8)
2 days/week	53 (16.8)	7 (13.2)	13 (24.5)	6 (11.3)	7 (13.2)
3 days/week	54 (17.1)	5 (9.3)	14 (25.9)	3 (5.6)	7 (13.0)
Total	316 (100)	25 (5.7)	74 (21.8)	22 (4.4)	38 (12.0)

A total of 22 taxi drivers were randomly selected from the 121 never smoked taxi drivers stratified by their taxi make/model, and drivers' age based on the information of the 316 responders. The demographic information of these twenty two drivers was summarized in Table 5.

Table 5 Personal Characteristics of Tested LA Taxi Drivers (n=22)

Age	47.05±13.76 (24, 47)
Male, n (%)	21 (95.45%)
Ethnicity	
Black, n (%)	4, (18.18%)
Hispanic/Latino, n (%)	0, (0%)
White, n (%)	6, (27.27%)
Asian, n (%)	7, (31.82%)
Other, n (%)	5, (22.73%)
Years as Taxi Driver	9.00±5.79 (2, 20)
BMI (kg/m²)	26.82±4.55 (19.51, 38.74)

4.1.2 Characteristics of Los Angeles taxi vehicles and driving behaviors

The data collected from the 316 recruitment forms showed that Ford Crown Victoria (31.6%), and Toyota Prius (26.6%) were the most popular taxi vehicle models, which comprised more than half of the surveyed taxi vehicles. Other vehicle models include Ford Escape (12.7%), Dodge Caravan (12.9%), Toyota Camry (7.3%), Chrysler Towncounty (3.5%), Chevy Uplander (1.6%), etc. Surveyed taxi vehicle model year ranged from 1987 to 2012, and 47% of the vehicles were more than 5 years old.

The survey also showed the average taxi driver occupation years as taxi drivers were 9.8 (mean) ±8.3 (SD). They work 11.9±2.3 hours a day, and 6.1±0.8 days a week. They spent 4.2 ±2.6 hours on freeways in each work day, and they kept the taxi vehicle windows open during 76.1±12.4% of their driving time.

4.1.3 Tested taxi cabs characteristics

Because of the stratified random selection method, the 22 tested taxis have a similar distribution of car model when compared with the surveyed results from the recruitment campaign. Toyota Prius and Ford Crown Victoria are the two most popular car models among Los Angeles taxi cabs. The five car models tested in this study (Toyota Prius, Ford Crown Victoria, Toyota Camry, Dodge Caravan, and Chevy Uplander) comprised of 86% of all types of taxi vehicle models in Los Angeles. The slightly over sampling of Toyota Prius is acceptable for this research because there is a trend and projection of more hybrid taxis in Los Angeles.

On average, the surveyed taxi cabs have higher mileages than a passenger vehicle of the same car age. As shown in Figure 3, a Los Angeles taxi cab has approximately twice as much mileage as a regular California passenger vehicle of the same car age in the study in Fruin, et. al. (2011). Therefore the taxi cabs are expected to have more wear and tear, and are likely to be leakier than regular passenger vehicles. It is reasonable to expect that, in general, AERs and I/O ratios of taxi cabs are substantially higher than those in regular passenger vehicles.

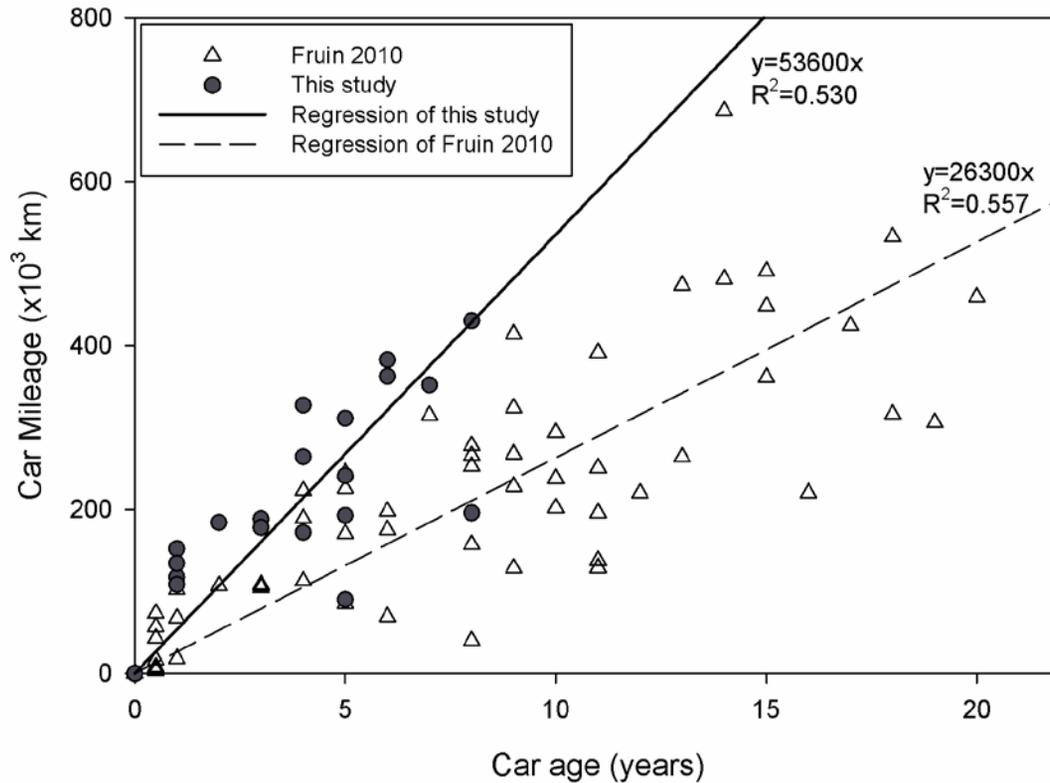


Figure 3 Relationship between car age and car mileage, comparing taxi cabs and representative passenger vehicles.

4.1.3 On-road and in-cabin UFP concentrations

When the taxi ventilation is under outside air (OA) mode or the windows are open, large amount of in-cabin air came from ambient very fast. In-cabin PM concentrations followed the on-road ambient concentration trend with a 30-60 second delay while vehicle air exchange rates ranged from 120-60 per hour (Zhu, Eiguren-Fernandez et al. 2007). Figure 4 showed the time series of the UFP number concentration sampling results of one of the tested taxis under Day1 test condition. Simultaneous on-road and in-cabin PM sampling results showed UFP levels inside the taxi cab followed its on-road trends. Because the taxi windows were controlled by the driver and almost always open through this sampling day, the in-cabin UFP concentrations were very similar to the on-road UFP levels.

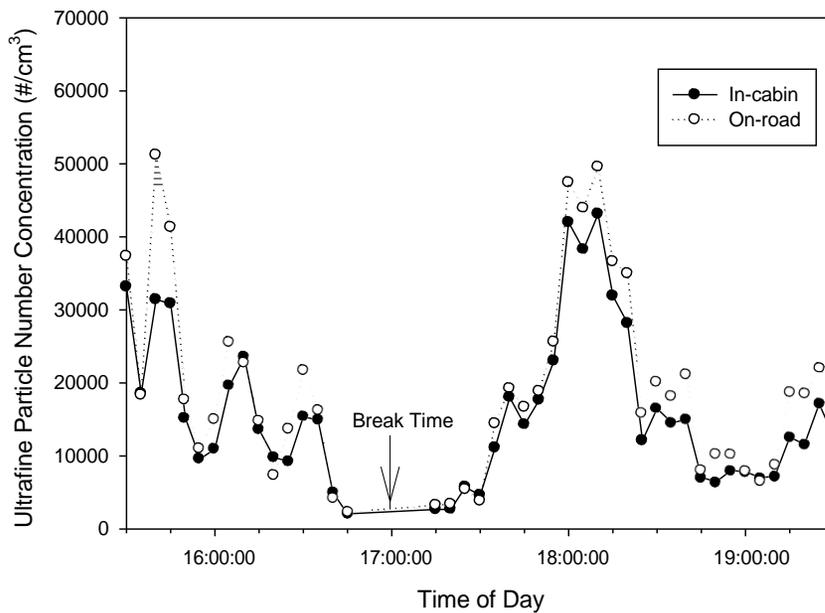


Figure 4 The time series of UFP sampling results when taxi windows were open and HECA filter or air purifier were not in use.

Figure 5 showed the UFP time series sampled when the taxi windows were closed, ventilation was set to OA mode at the medium fan level, with HECA filter in use. The figure showed the in-cabin UFP concentrations were still following the on-road pattern, but the levels were much lower than the on-road UFP concentrations.

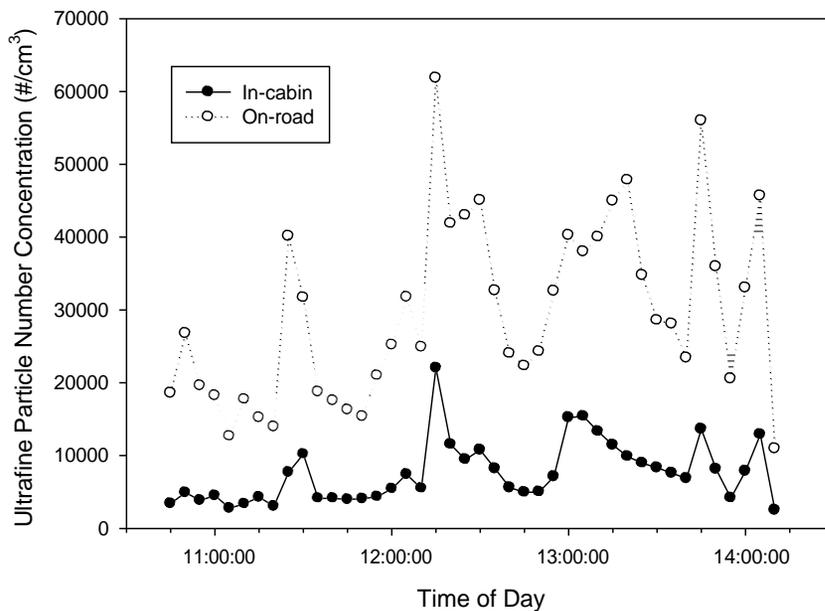


Figure 5 Time series of UFP sampling results when taxi windows were kept closed, and ventilation was set to OA mode, and HECA filter was in use.

Comparing the two time series patterns of UFP number concentrations in Figure 4 and Figure 5, the on-road UFP number concentrations both spiked up to around 6.0×10^4 /cm³. However, when the car windows were open but without HECA filter or air purifier in use, the in-cabin UFP concentrations peaked at 4.5×10^4 particles/cm³. When the car windows were closed and the HECA filter was in use, the in-cabin levels peaked at 2.5×10^4 particles/cm³. These results showed controlling the taxi vehicle windows and HECA filter application were very helpful for reducing the taxi in-cabin UFP concentrations.

4.1.4 On-road UFP concentration influencing factors

Previous studies showed that the on-road UFP concentration typically ranges from 1×10^5 to 5×10^5 particles/cm³, one or two orders of magnitude higher than a typical ambient level in an urban environment (Somers, McCarry et al. 2004; Zhu, Eiguren-Fernandez et al. 2007; EPA 2012). In Los Angeles, regular commuters' in-cabin exposure alone accounts for up to 45-50% of their total daily exposure to UFPs (Zhu, Eiguren-Fernandez et al. 2007; Fruin, Westerdahl et al. 2008). Considering taxi drivers' prolonged on-roadway work time, their higher in-cabin exposure was primarily driven by the elevated on-road UFP levels.

The on-road data collected from the taxi sampling campaign, showed similar UFP ranges from 10^5 to 5×10^5 particles/cm³. To analyze the impact of traffic on the on-road levels, daily average total traffic volume and heavy duty diesel vehicle (HDDV) volume were downloaded from CalTrans PeMS system. The Mainline VDS 718300 dataset was because it was collected at the closest monitoring station to UCLA, where the sampling started and completed. The daily averages of on-road sampling results were log and plotted against the total traffic volume and HDDV volumes. Moderate linear were detected with R²s of 0.24 and 0.31 for total traffic and HDDV, respectively (Figure 6).

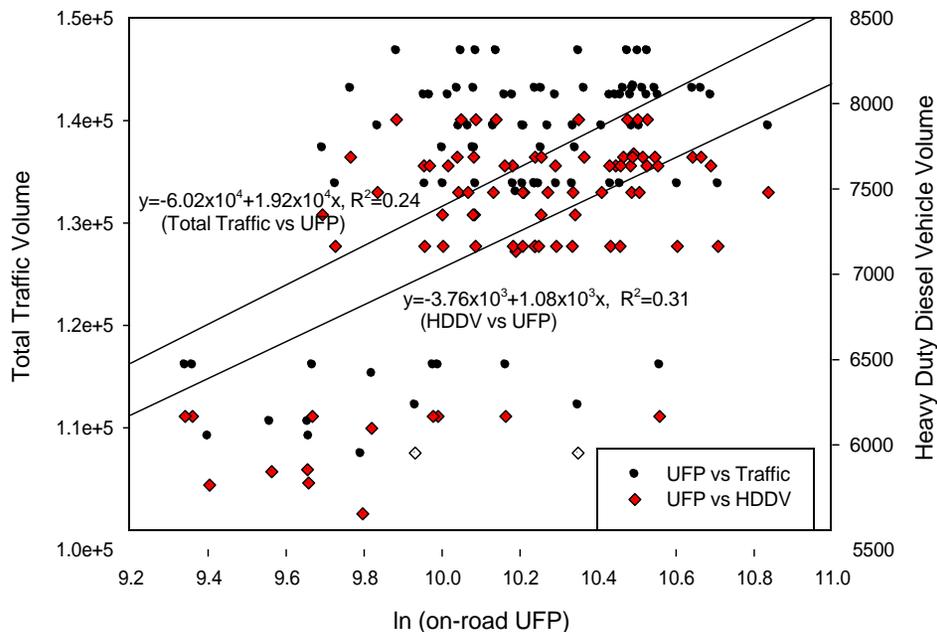


Figure 6 On-road UFP number concentrations and correlations with total traffic, HDDV volumes.

To investigate the effects of vehicle speeds and locations on on-road UFP concentrations, the on-road UFP sampling data were grouped by freeways and local streets. The geometric mean UFP concentrations in these two groups were compared and found to be significantly different with a group t-test ($p=0.00$) (Figure 7).

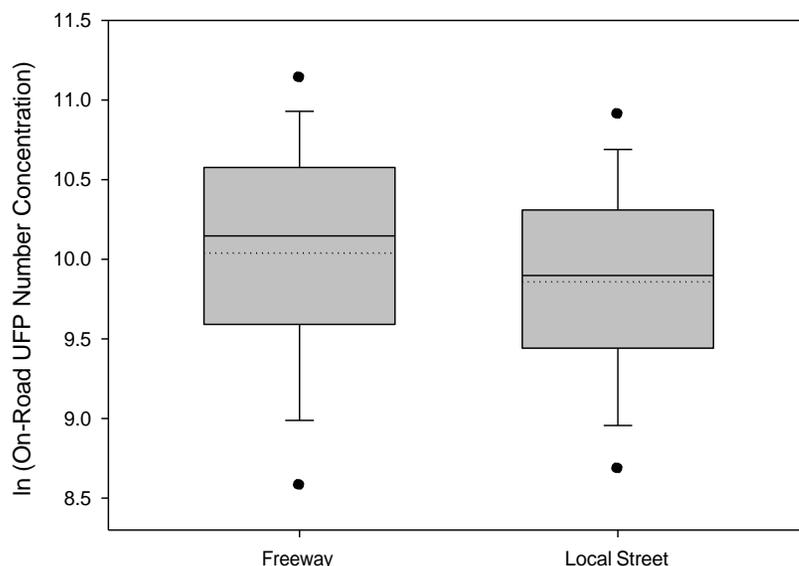


Figure 7 Log-transformed on-road UFP concentration comparison between freeways and local streets. The dot lines inside the boxes showed the means, and the solid lines inside the boxes showed the medians. The boundaries of the boxes showed the quartiles of the data, and the whiskers indicated the 10th and 90th percentiles. The dots showed the 5% and 95% percentiles.

Pearson’s correlation coefficients were calculated between log transformed on-road UFP number concentrations and vehicle speeds. Only very low or no correlation were detected and summarized in Table 6. That means the instant vehicle speed doesn’t affect the UFP concentrations on roadways.

Table 6 Summary of Pearson’s Correlations between log transformed UFP concentrations and speeds (R^2 s)

	R^2 with Log transformed UFP levels
Freeway speed	0.13
Local street speed	0.04
Overall speed	0.11

4.1.5 Taxi UFP I/O ratio analysis

The in-cabin and on-road UFP concentrations were automatically logged every second during the taxi tests. However, since the data at the adjacent time points are highly correlated, five minute average concentrations were calculated from the logged data and used for I/O ratio analysis. For example, the instant I/O ratios were calculated from the five minute average UFP on-road concentrations divided by the five minute average UFP in-cabin concentrations.

Each taxi vehicle was tested for four consecutive days with different window/ventilation and HECA filter/purifier availabilities (Table 2). The calculated I/O ratios were grouped to these four test conditions and

Figure 8 showed the box plots of the four groups. ANOVA tests showed the four different test conditions made the average I/O ratios significantly different ($p=0.00$). The lowest average UFP I/O ratios showed on the third test day, when the taxi windows were closed and the HECA filter were in use.

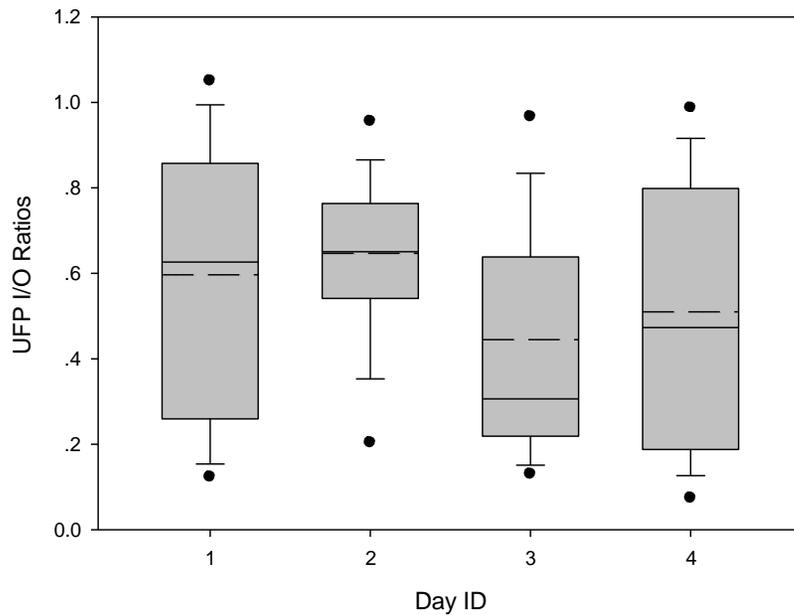


Figure 8 Box plots of UFP concentration I/O ratios on different test days. The dash line inside the boxes showed the means, and the solid lines inside the boxes showed the medians. The boundaries of the boxes showed the quartile of the data, and the whiskers indicated the 10th and 90th percentiles. The dots showed the 5% and 95% percentiles.

Histogram plots in Figure 9 indicated that, on the testing days when the taxi window was controlled by the driver, the UFP concentration I/O ratios showed bimodal distributions. Only the data of I/O ratios between 0 and 1 were selected for plotting the histograms because there were only 5% of the data points were above 1. If we don't exclude those data points which were higher than 1, the histogram will spread out extensively. On the testing days when the windows were closed, the distributions of I/O ratios showed single mode only.

On Day1 and Day4 the taxi windows were controlled by the driver and could be either open or closed. The two modes of the histograms showed the window open and close situations. The plot of Day1 showed that when the taxi windows were open, the I/O ratios were mainly between 0.8 and 1, and when the windows were closed and car ventilation was set to RA mode, the I/O ratios mainly ranged between 0.1 and 0.3. The plot of Day4 is similar with Day1. However, the window was closed all the time on Day2 and Day3. The I/O ratio histograms showed single modes on these two days. On Day2, the mode was between 0.6 and 0.8. On Day3, the mode was between 0.2 and 0.4. The only difference on the tests of these two days was HECA filter/purifier availability. These histograms roughly showed the HECA filter/purifier reduced 1/2 to 2/3 UFP I/O ratios from no filter or OEM filter in use scenarios. Also on Day2 and Day3, the modes of I/O ratios did not stay between 0.1 and 0.3 as the first modes on Day1 and Day4,

because the taxi ventilation was set to OA mode on Day2 and Day3, but the it could be set to RA mode on Day1 and Day4 because the drivers were controlling the ventilation and window positions. The I/O ratios could be fairly low when the vehicle ventilation is under RA mode.

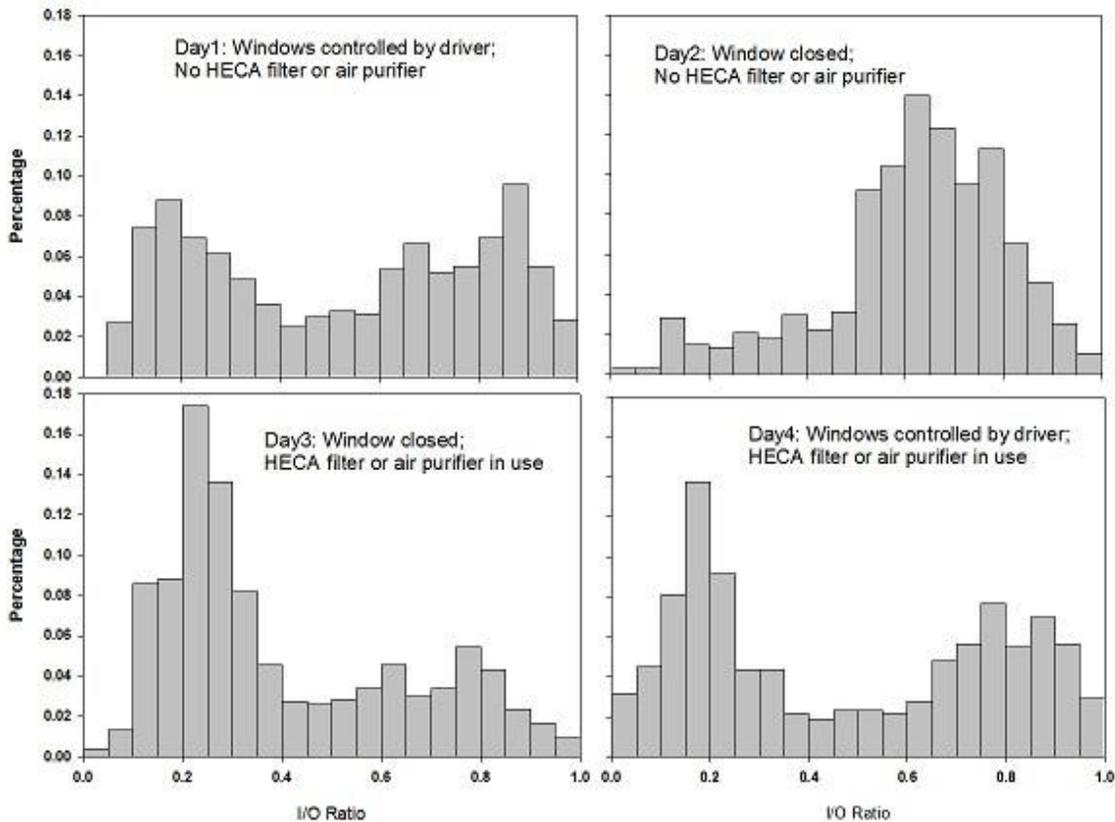


Figure 9 Histograms of UFP I/O ratio distributions under different test settings.

The on-road UFP concentrations are often higher on freeways than on local streets, while the average vehicle speeds are also higher in most of the cases. However, from our sampling data, the I/O ratios were not significantly different between driving on freeway and local streets (Figure 10). Also the speeds apparently did not correlate with I/O ratios.

The average UFP I/O ratios of each tested taxi vehicle were compared with the mileage (odometer reading) of each taxi vehicles on the first test day. Because the Ford Crown Victoria cabs were obtained from retired police cars, the ages and odometer readings were rather higher than other models. A linear regression line with a R^2 of 0.56 was fitted to all of the observations (Figure 11).

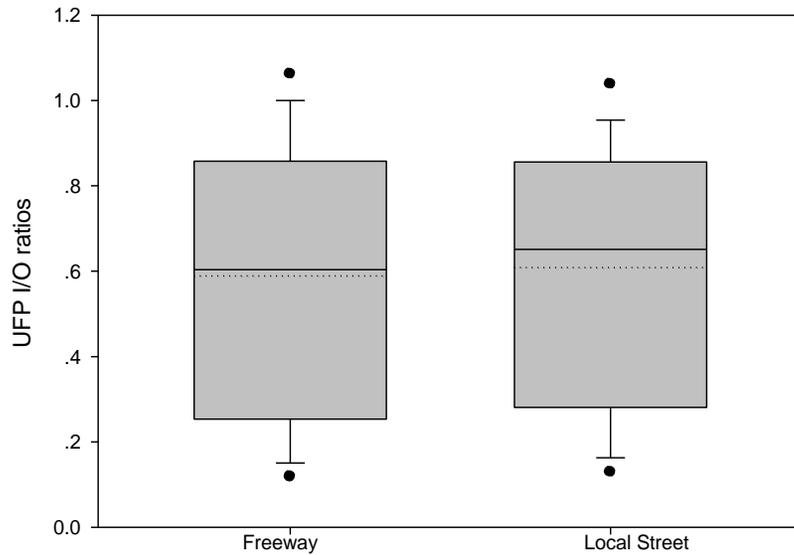


Figure 10 Comparison of ultrafine particle I/O ratios between driving on freeways and local streets. The dot lines inside the boxes showed the means, and the solid lines inside the boxes showed the medians. The boundaries of the boxes showed the quartile of the data, and the whiskers indicated the 10th and 90th percentiles. The dots showed the 5% and 95% percentiles.

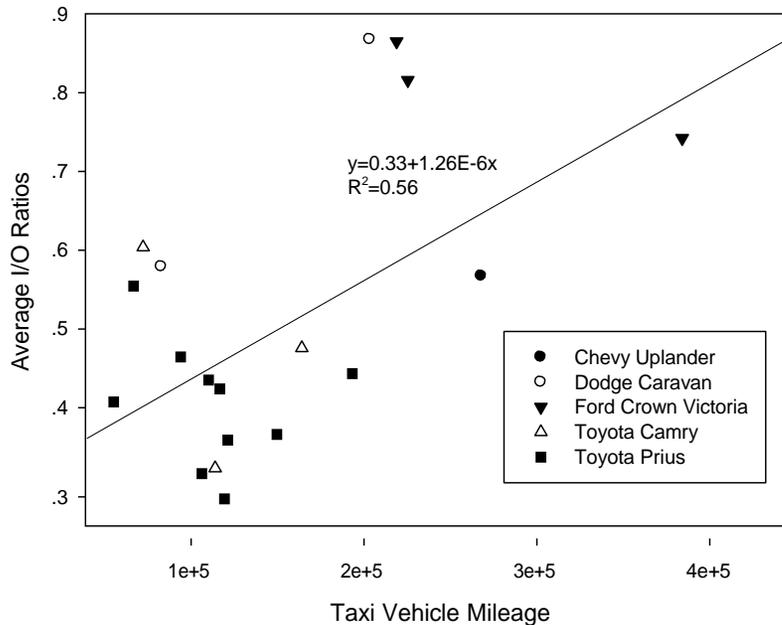


Figure 11 Effects of taxi mileage on ultrafine particle in-cabin to on-roadway (I/O) ratios.

The observed I/O ratios for each taxi cab with respect to different make/model in different test days were summarized in Table 7 and Figure 12. A mixed effect model was fitted for the data and the fixed effect was reported in the following table (Table 8).

Table 7 Summary of UFP and PM_{2.5} I/O Ratios for Tested Taxis

Taxi Vehicle Model	UFP I/O Ratio (Mean, SD)				PM _{2.5} I/O Ratio (Mean, SD)			
	Day 1	Day 2	Day 3	Day 4	Day 1	Day 2	Day 3	Day 4
Chevy Uplander	0.56 (0.34)	0.24 (0.14)	1.00 (1.34)	0.58 (0.39)	NA	0.39 (0.10)	0.61 (0.13)	0.58 (0.15)
Dodge Caravan	0.93 (0.62)	0.64 (0.15)	0.40 (0.24)	0.72 (0.20)	0.90 (0.20)	0.83 (0.30)	0.67 (0.33)	0.86 (0.13)
Ford Crown Victoria	0.83 (0.22)	0.79 (0.17)	0.79 (0.25)	0.87 (0.24)	0.73 (0.13)	0.71 (0.16)	0.67 (0.16)	0.66 (0.16)
Toyota Camry	0.75 (0.37)	0.55 (0.25)	0.31 (0.13)	0.49 (0.32)	0.66 (0.32)	0.86 (0.23)	0.50 (0.11)	0.69 (0.28)
Toyota Prius	0.43 (0.33)	0.63 (0.23)	0.26 (0.20)	0.34 (0.30)	0.73 (0.39)	0.90 (0.33)	0.40 (0.20)	0.54 (0.30)

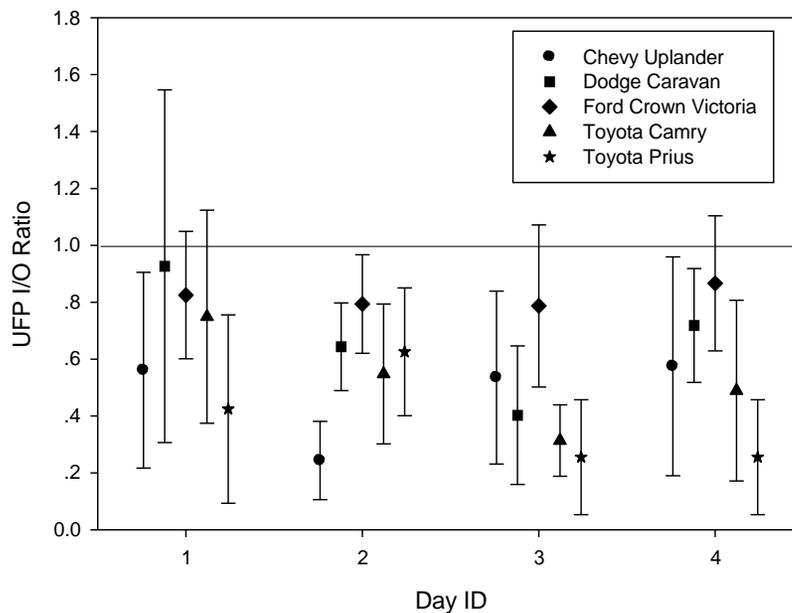


Figure 12 I/O ratios of different taxi vehicle make models on different test days. Central dots showed the means, and error bars showed 1 standard deviation.

4.1.6 Modeling in-cabin UFP levels

A mixed effect model was fitted to the taxi vehicle sampling data to explore the combined effects of different factors on the UFP levels inside taxi cabin. The model can be expressed in an equation as:

$$\log(i\text{-cabin UFP concentration}) = \mu + \beta_1 + \beta_2 * i + \beta_3 * \text{Mileage} + \beta_4 * \text{Freeway} + \beta_5 * \text{Mileage} * \text{Freeway} + \beta_6 * \text{Day} + \beta_7 * \text{Chevy Uplander} + \beta_8 * \text{Dodge Caravan} + \beta_9 * \text{Ford Crown V.} + \beta_{10} * \text{Toyota Camry} + \beta_{11} * \text{Toyota Prius} + \epsilon$$

(Equation 3)

The outcome of this model is the log transformed in-cabin UFP number concentrations. The random intercepts b_i reflected the variability of car models. Fixed effect terms include the different interventions during the four test days for each taxi vehicle (Table 2), the vehicle mileage, whether driving on freeways or not, and the interaction between mileage and driving on freeways or not. ϵ is the random error term. The coefficient estimations and the significance levels were summarized in Table 8. Dummy variables were created for different interventions on different testing days. Day4 were used as reference group. In addition to the calculations for p-values of all estimates, the type 3 tests are also performed for fixed effects estimates with SAS to minimize the interference from the random effects. The parameter estimates in Table 8 can be plugged into **Error! Reference source not found.** as coefficients of each factor. For example, if holding everything else constant, when the taxi vehicle mileage increased 1 mile, log (in-cabin UFP concentration) would decrease by $1.36 * 10^{-6}$.

Table 8 Estimates of the mixed effect model coefficients

Fixed Effects	Estimate	p-value	Type 3 test
Intercept	9.32	0.00	NA
Day1	0.15	0.00	0.00
Day2	0.44	0.00	0.00
Day3	-0.26	0.00	0.00
Mileage	-1.36E-06	0.00	0.00
Freeway	7.30E-02	0.32	0.32
Mileage*Freeway	8.63E-07	0.00	0.05
Random Effects			
Chevy Uplander	-0.50	0.05	NA
Dodge Caravan	0.44	0.08	NA
Ford Crown V.	0.73	0.00	NA
Toyota Camry	-0.22	0.38	NA
Toyota Prius	-0.44	0.08	NA

4.2 Aim 2 Exposure mitigation by HECA filters

The effects of mitigation strategy, in this case the HECA filtration, on reducing taxi drivers' occupational exposure to UFPs was assessed, by comparing the in-cabin concentrations and I/O ratios on days with OEM filter and with HECA filter.

4.2.1 Comparison on in-cabin concentrations

The results of student t-test on UFP concentrations with OEM and HECA filters are shown in Figure 13, which indicates that, when the drivers were required to keep windows closed (on day 2 and day 3), the HECA filter reduced the in-cabin UFP concentrations significantly (p -value less than 0.001). While on the days when the drivers have control on the windows positions (day 1 and day 4), the HECA filter did not reduce the in in-cabin UFP concentrations as compared to OEM filter. This finding suggested that if taxi drivers can keep their cab windows closed as much as possible, the HECA filter could better protect them from UFP exposure.

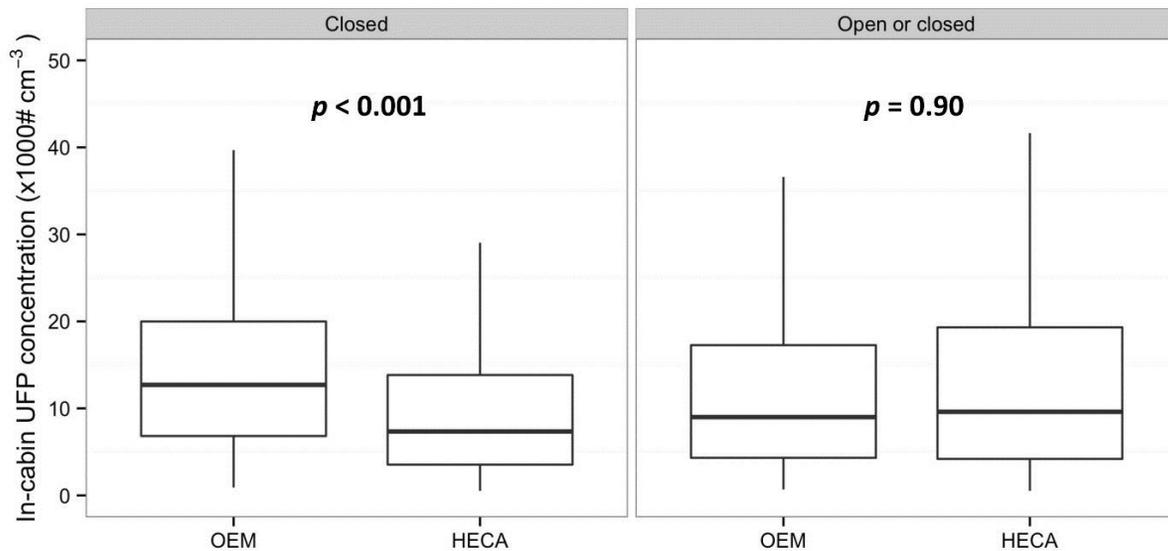


Figure 13 Comparison of in-cabin UFP concentrations with OEM and HECA filters with different window positions

4.2.2 Comparison of I/O ratios

Compared to the actual in-cabin UFP concentrations, the UFP I/O ratio would be a better index to use to compare the UFP removal efficiency of filters. The results of student t-test on UFP I/O ratios with OEM and HECA filters are shown in Figure 14, which indicates that, under either window conditions, the HECA filter can reduce the UFP I/O ratio significantly (p -value less than 0.001 for both conditions). This finding suggested that, using HECA filter in taxi cabs is an effective method to mitigate taxi drivers' occupational exposure to UFPs. But still, keeping the cab windows closed as much as possible (left panel) would result in a larger difference between UFP I/O ratios, when compared with that if the windows position are not controlled (right panel).

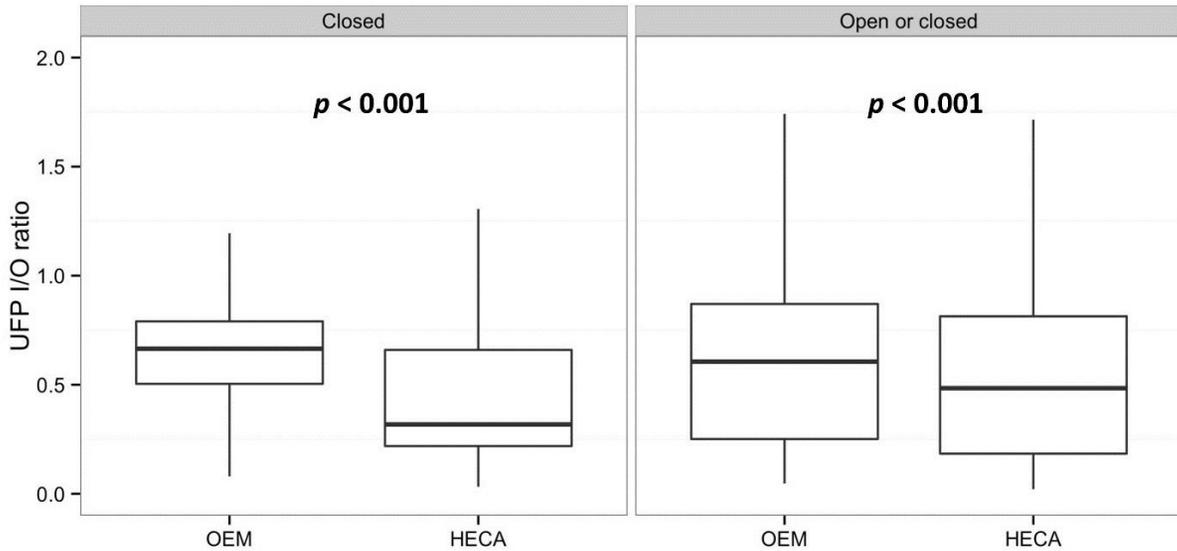


Figure 14 Comparison of UFP I/O ratios with OEM and HECA filters with different window positions

4.3 Analysis beyond the Proposed Two Aims

4.3.1 Air exchange rates in taxi cabs

The AERs measured in taxi cabins were summarized in Table 9. It shows that the model of Crown Victoria have highest mean AERs of 75.2 h^{-1} , which is approximately as four times as the lowest mean AERs of 18.9 h^{-1} observed from Caravan and Prius models. This finding suggests that the car model would substantially affect the AERs experienced by taxi drivers. Figure 15 shows the relationship between log-transformed AERs with the driving speed. In general, taxi driving speeds (the x-axis) had two modes corresponding to the driving on local streets and freeways, which is typical for urban traffic conditions. The log-transformed AERs (the y axis) also had two modes, one of which had higher value and higher frequency than the other.

Table 9 Summary of characteristics of air exchange rates measured in tested taxi cabs

Car Model	Number of Vehicles	AER [h^{-1}]				
		n*	Mean	25%	50%	75%
Camry	3	528	37.0	14.7	41.3	82.3
Caravan	3	502	18.9	13.6	24.0	32.8
Uplander	1	158	26.8	16.4	28.2	49.4
Crown Victoria	5	1126	75.2	41.3	78.3	148.4
Prius	10	2057	18.9	7.1	25.5	39.6

* Number of 5-min average AER values.

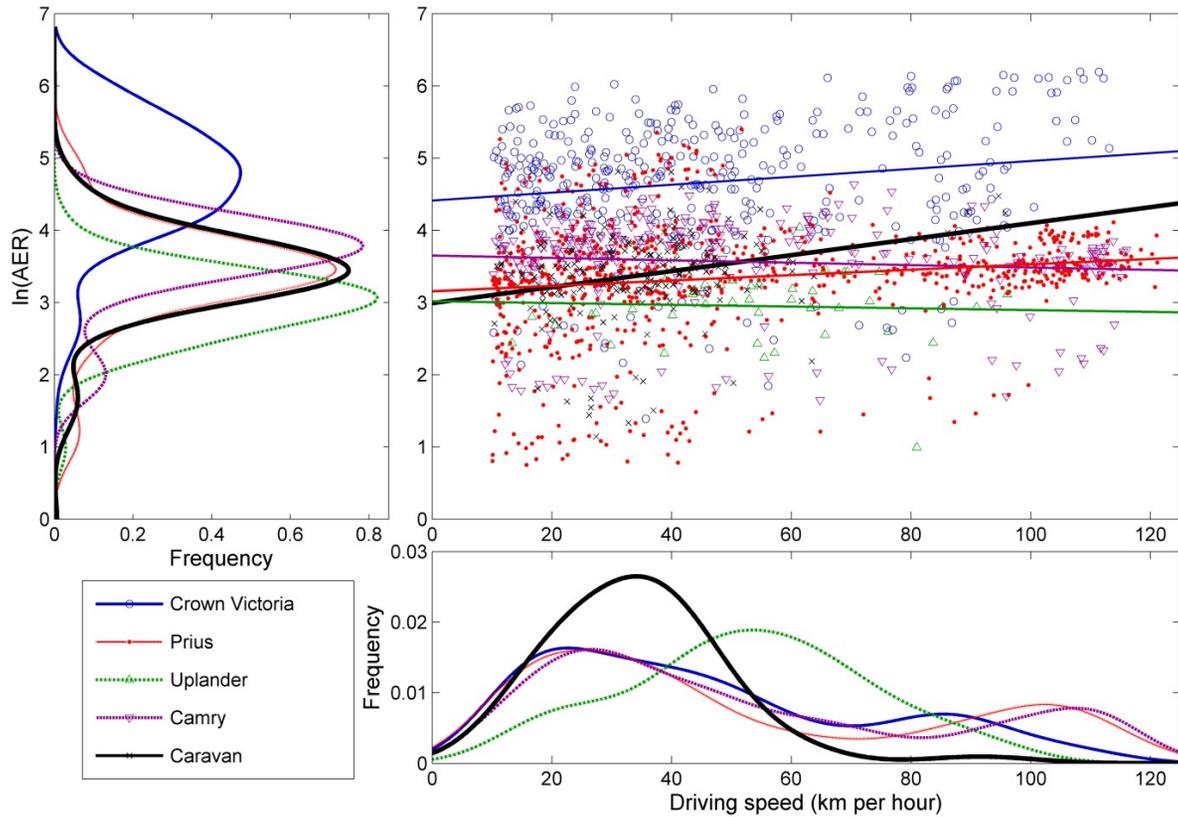


Figure 15 Log-transformed air exchange rates and its relationship with driving speed, grouped by car models.

By using the GPS data, each AER data point was identified for whether it is obtained while driving on a freeway or a local street. Then student t-test results showed that there is a significance difference between the AERs on freeways and on local streets. This finding suggests that the more time a taxi driver spend on freeways, the higher AERs he/she will experience.

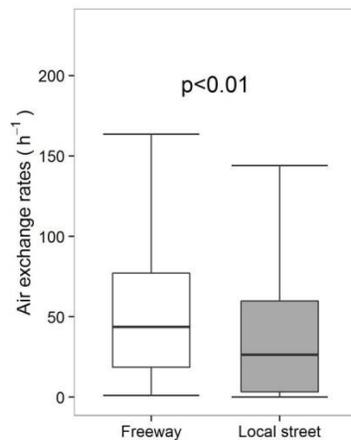


Figure 16 Comparison between air exchange rates obtained from freeways and local streets

The GEE modeling results are shown in Table 10. The GEE model provided generalized estimates of linear model, taking the individual-specific effect of each taxi cab/driver combination into consideration. The modeling results showed large intercepts, which indicated that AERs are generally high. The *Speed*, *CarAge*, and *Mileage* all had *p*-value greater than 0.05, meaning they are not statistically significant factors in determining the AERs in taxi cabs. However, the *Speed* and *CarAge* were positively correlated with AERs, which is consistent with the finding that when taxi cabs had higher AERs when driving on freeways, where the speed was also higher, compared to those on the local streets. It is consistent with the findings in previous studies on passenger vehicles (Park, Spengler et al. 1998; Fruin, Hudda et al. 2011). The reason that speed was not statistically significant in this study was that the experiment conditions used in previous studies and this study were different. Those previous studies used well-controlled experiment conditions, i.e. closed-window, recirculation ventilation, and stable driving speed, aiming to understand the mechanisms of in-vehicle air exchange and its determining factors. For example, in the Fruin et al. (2011) study, the AERs inside regular passenger vehicles under “nearly constant driving speed” were treated as a constant value, since other factors such as windows position and ventilation settings were fixed. This study, instead of studying the underlying mechanisms of air exchange in vehicles, aimed to quantify the actual AERs in taxi cabs during taxi drivers’ representative working conditions, under which all the aforementioned factors are frequently changing. That is why the AERs measured in this study had large variability (with a geometric standard deviation of 3.3) and therefore the statistical significance of speed was reduced. The highly variable AER data suggested that the taxi drivers’ occupational exposure to TRAP is also highly variable, even within a same workday.

Table 10 Coefficients of Generalized Estimating Equations model for AERs measured under RD condition

	Estimate	Std. Err.	<i>p</i> -value
Intercept	3.026	0.306	<0.001
Speed	0.003	0.002	0.142
CarAge	0.039	0.069	0.574
Mileage	-0.002	0.002	0.201
CarModel: Prius ¹	0	0	
CarModel: Camry	0.714	0.480	0.137
CarModel: Caravan	0.252	0.320	0.634
CarModel: Uplander	0.793	0.378	0.036
CarModel: Crown Victoria	2.305	0.341	<0.001

a. Prius was used as the reference category therefore its estimate and standard deviation were both zero.

On the other hand, the modeling results suggested that the AERs measured in two models of taxi cabs, Uplander and Crown Victoria, whose manufacturers were GM and Ford respectively, had significantly higher AERs than those measured in other three models, two of which were manufactured by Japanese companies. Interestingly, this is consistent with one of previous studies which demonstrated that the regular passenger vehicles manufactured by GM and Ford also had significantly higher AERs than vehicles manufactured by Japanese companies (Fruin, Hudda et al. 2011). The reasons for this cross-brand different in AERs are outside of the scope of this study and deserve further investigation. The data obtained in this study provided more ‘realistic’ information about the actual AERs the taxi drivers experience in their daily work and can be linked to their occupational exposure assessment in further studies.

4.3.2 Urine biomarker analysis

The results of the urinary monohydroxylated PAH metabolites analysis showed that, within the total of nine analyzed metabolites, four of the mean levels in the taxi driver group were higher than the control group significantly with group t tests ($p < 0.05$) (Table 11). These four metabolites were 1- and 2-NAP, 1-PYR and 9-FLU. The results were also comparable to the US population urinary metabolites levels found from the National Health and Nutrition Examination Survey (NHANES) database. The data was from Li, et al (Li, Romanoff et al. 2012).

Because 1-PYR is the most commonly used urinary PAH biomarker, taxi driver urinary 1-PYR data were used as the biomarker of their PAH exposure and further analyzed. A longitudinal model was developed to find out the associations between urinary 1-PYR and their PM exposure. By plotting the histograms, urinary 1-PYR results were found not normally distributed but positively skewed. 1-PYR data were log transformed for the correlation analysis and model development. UFP and $PM_{2.5}$ were also log transformed for the same reason. The log transformed variables IPYR, IUFP and IPM were used for the final model fitting instead of the original variables of 1-PYR, UFP and $PM_{2.5}$. Eight time points were created by defining the first urine sample collection time as 0, and the second sample collection time point as 6 (hour), and so on for the other 6 samples collected on the second, third and fourth sampling day.

Comparing models with different covariance structure, the linear mean structure with unstructured covariance showed fitting the data best. Other possible factors such as age, years as taxi driver, time, shift time and urine creatinine levels were included into the model and showed significant results. The solutions, estimate p-values and the type 3 tests for final model showed all parameters significant. The coefficient estimates and the test results were shown in Table 12 and the estimated parameters were all significant at .05 levels. An example for interpreting the final longitudinal 1-PYR model can be, holding other effects fixed, when working as driver for 1 more year, the urinary log (1-PYR) levels increase 0.14.

Table 11 Creatinine Adjusted Urinary OH-PAH Concentrations of Tested Taxi Drivers (µg/g)

Analyte	abbr.	LA Taxi Driver Group (n=164)				UCLA Control Group (n=122)				US Population (NHANES)**	
		Mean	Median	Max	Min	Mean	Median	Max	Min	Median	95th
*1-hydroxynaphthol	1-NAP	2.28	1.02	16.90	0.02	0.99	0.60	5.42	0.02	1.56	17.80
*2-hydroxynaphthol	2-NAP	5.20	3.75	21.90	0.64	3.68	1.92	36.16	0.02	1.94	16.70
1-hydroxyphenanthrene	1-PHE	0.15	0.13	0.86	0.01	0.16	0.13	0.25	0.03	0.09	0.43
2-hydroxyphenanthrene	2-PHE	0.06	0.05	0.43	0.01	0.06	0.04	0.07	0.01	0.06	0.35
3-hydroxyphenanthrene	3-PHE	0.09	0.07	0.89	0.02	0.11	0.06	0.15	0.02	0.05	0.23
*1-hydroxypyrene	1-PYR	0.13	0.09	0.90	0.02	0.11	0.07	0.90	0.01	0.04	0.24
2-hydroxyfluorene	2-FLU	0.24	0.18	1.98	0.06	0.07	0.05	0.56	0.01	0.21	0.85
3-hydroxyfluorene	3-FLU	0.13	0.09	1.57	0.02	0.13	0.08	0.27	0.01	0.09	1.06
*9-hydroxyfluorene	9-FLU	0.42	0.34	1.83	0.08	0.26	0.20	0.21	0.07	0.24	1.89
Total monohydroxylated NAP	∑OHNAP	7.47	6.29	38.80	0.70	4.67	2.73	38.53	0.22	3.50	34.50
Total monohydroxylated PHE	∑OHPHE	0.30	0.25	1.97	0.04	0.71	0.55	1.13	0.15	0.20	1.01
Total monohydroxylated FLU	∑OHFLU	0.79	0.63	5.28	0.17	0.33	0.26	0.46	0.08	0.54	3.80
malondialdehyde	MDA	38.24	31.62	273.42	0.22	39.48	32.92	228.67	0.52	N/A	N/A

*Significant differences detected by group t-tests.

**US population levels were from National Health and Nutrition Examination Survey (NHANES) database.

Table 12 1-PYR Model Parameter Estimates

Effect	Estimate of Coefficient	P value
Intercept	3.48	0.00
Age	-0.04	0.00
Year as Driver	0.14	0.00
Shift time	0.17	0.00
Time	-0.01	0.00
Creatinine	0.09	0.00
IUFP	0.21	0.00
IPM	-0.48	0.00

4.3.3 Blood pressure and heart rate variability

Taxi drivers' blood pressure (BP) and heart rate variability (HRV) were also monitored during the field tests to explore the acute health effects of their occupational exposure. The descriptive statistics of taxi drivers' BP data are shown in Table 13. The mean systolic pressure at work was 3.7 mmHg lower than the mean systolic pressure while the drivers were not at work, and the difference is statistically significant. This is consistent with other studies, which also found that people from different occupations have higher ambulatory blood pressure during their work (Schnall, Schwartz et al. 1998; Goldstein, Shapiro et al. 1999), Figure 17 shows the comparison of BP for each individual driver.

Table 13 Descriptive statistics of blood pressure

	Blood Pressure [mmHg]				
	Number of readings	Mean	25% quantile	median	75% quantile
Systolic Pressure					
At work	803	126.5	113	125	137
Not at work	225	122.8	111	120	131
Diastolic Pressure					
At work	803	77.8	69	77	86
Not at work	225	77.9	70	79	85

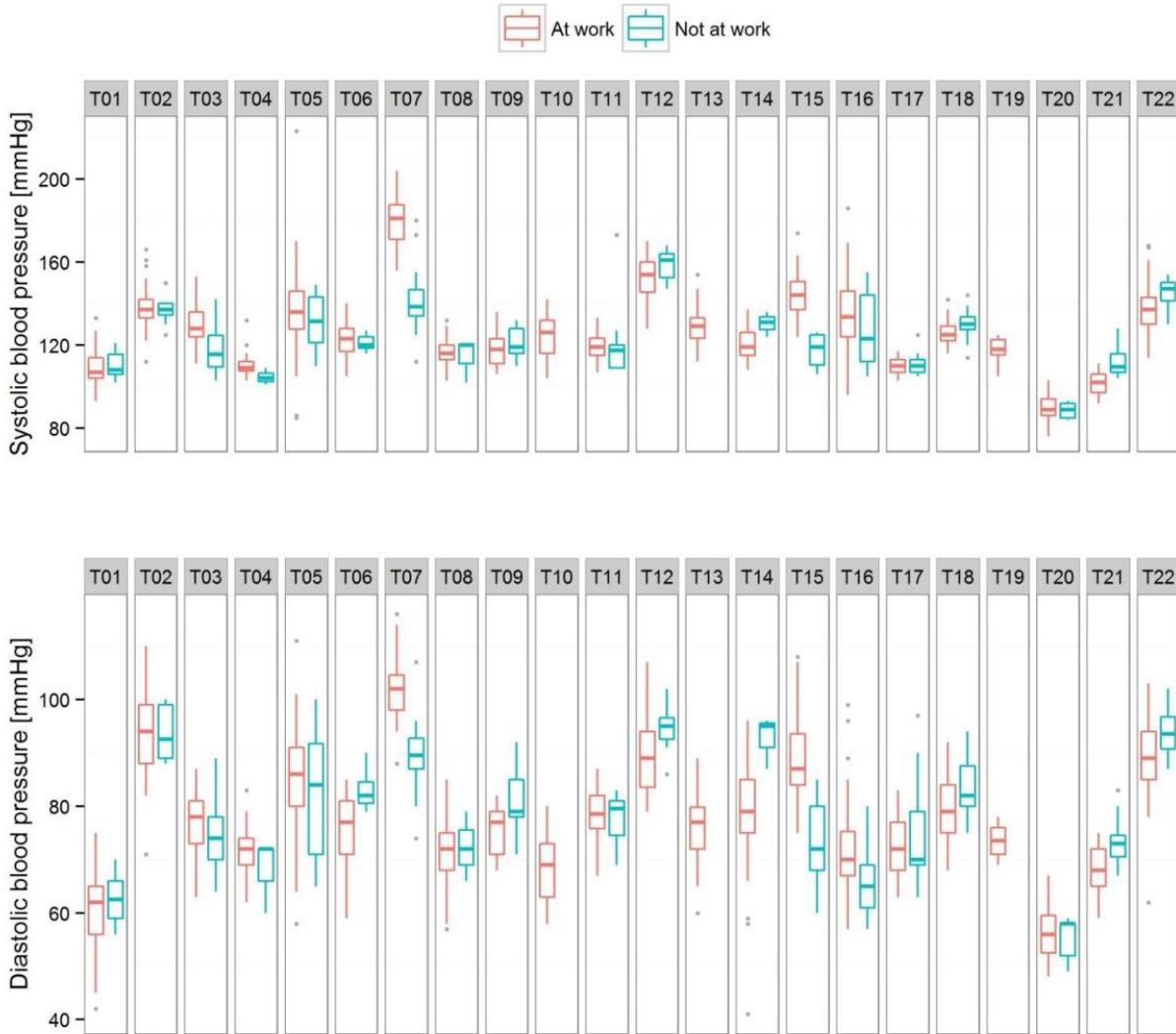


Figure 17 Comparison between blood pressure under at work and not at work conditions. Each pair of boxes refers to one driver, indicated by the IDs such as T01, T02 and so on.

The Table 14 shows the description statistics of taxi drivers' heart rate variability, environmental factors, and air pollutant levels measured during all tests. Two taxi drivers (T05 and T19) only had a few HRV data recorded and therefore their data were not included in this analysis. One taxi driver (T20) was the only female driver in this study and her HRV data were not included in this analysis in order to reduce the level of complexity of statistical analysis. Figure 18, Figure 19, and Figure 20 show the three representative HRV indexes, RMSSD, pNN50, and LF/HF Ratio data obtained from individual driver, respectively.

Table 14 Descriptive statistics of heart rate variability outcomes, environmental factors, and exposure concentrations.

	# of obs.	Mean	SD	Min	Max
Demographics					
Age (year)	19	47.4	13.9	24	67
Years as Taxi Driver (year)	19	9.4	6.4	0.5	20
BMI (kg/m ²)	19	26.4	4.2	19.5	38.7
Environment factors					
Temp (degree C)	794	26.0	3.7	16.5	39.9
Relative humidity (%)	794	40.5	11.7	18.5	78.6
Driving speed (km per h)	816	42	30	1	117
Exposure					
PM _{2.5} (ug/m ³)	782	20.7	12.6	2.3	137.2
UFP (particles/cm ³)	750	15800	16500	1000	150000
Leq (dBA)	787	69	4	49	81
CO ₂ (ppm)	794	1120	760	430	4700
HRV outcomes					
Mean HR (beats/min)	816	83	14	52	149
MRR (msec)	816	762	108	449	1607
StdRR (msec ²)	816	88	111	4	1180
RMSSD (msec)	816	46	43	2	329
pNN50 (%)	816	15.5	17.8	0.0	92.7
LF (msec ²)	816	4700	65000	2	1925700
HF (msec ²)	816	1800	21700	1	641300
LF percent	816	27.70	15.65	0.64	79.77
HF percent	816	14.31	12.00	0.08	69.09
LF/HF Ratio	816	3.18	2.61	0.17	24.68
Total Power (msec ²)	816	27800	182800	12	3813500

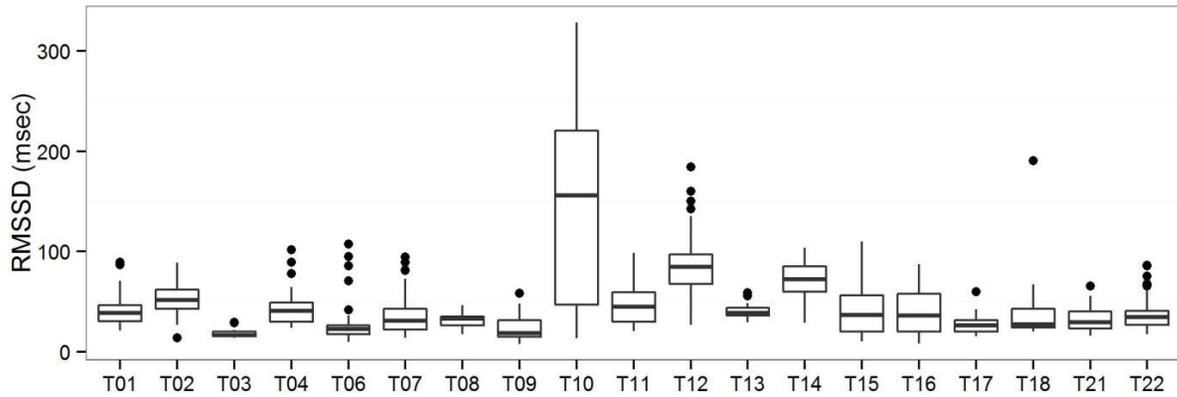


Figure 18 Boxplot of RMSSD data obtained from individual driver

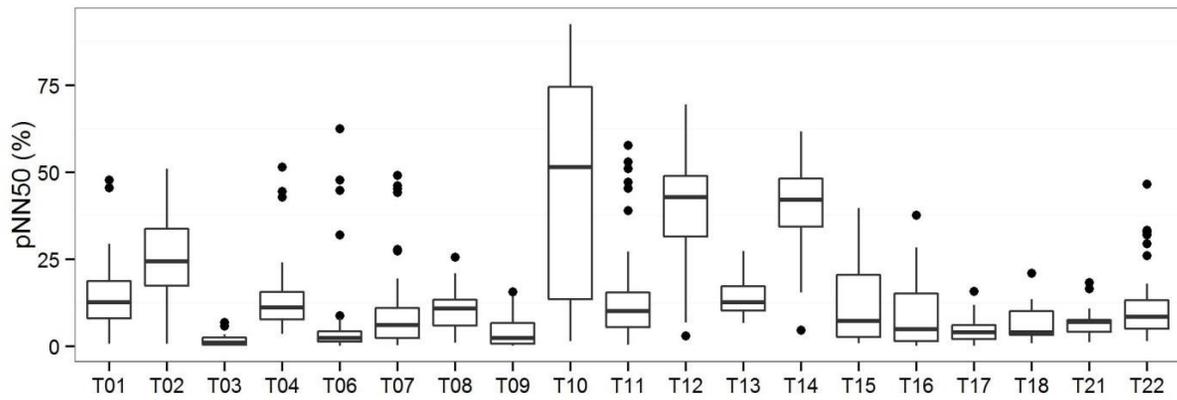


Figure 19 Boxplot of pNN50 data obtained from individual driver

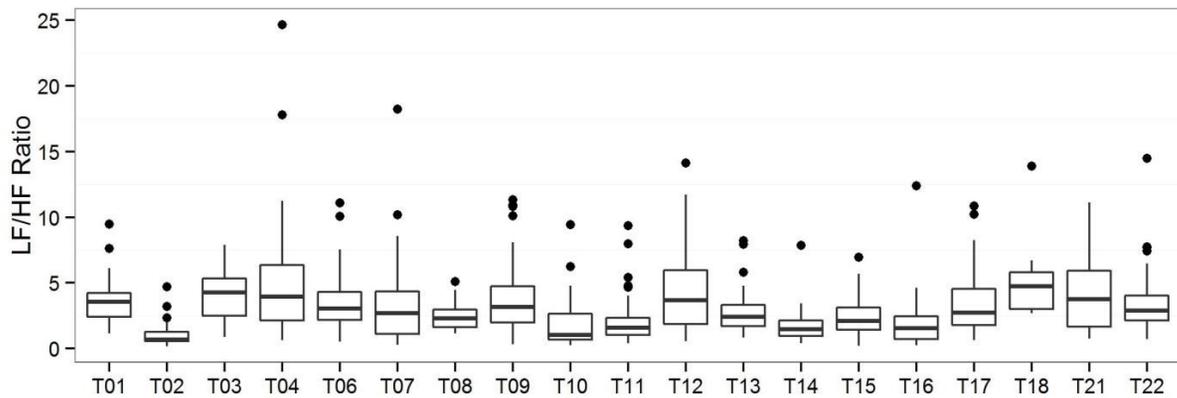


Figure 20 Boxplot of LF-to-HF ratio data obtained from individual driver

The statistical data analysis on these HRV data is still on-going. We plan to publish these data, analysis, and findings in peer-reviewed journals later.

5. CONCLUSIONS

Twenty two taxi drivers in the Greater Los Angeles area in California were recruited in this study. We worked with each of them to collect the air pollutant data, environmental factor (i.e. temperature, humidity, and noise level) data, and the health indicator (i.e. ambulant blood pressure and heart rate) data. For each driver, one experiment consisted of four consecutive test days with one driver and his/her taxi cab. On each test day, the driver drove 6 hours in the Greater Los Angeles area as he or she would typically do. One field technician rode along in the taxi cab operating and maintaining all the sampling instruments.

The two specific aims of this study were fulfilled by quantifying the on-road and in-cabin UFP concentrations and by testing the difference in in-cabin UFP concentrations and UFP I/O ratios with OEM cabin air filter and with HECA air filter. The on-road data collected from the taxi sampling campaign, showed UFP concentration ranges from 10^5 to 5×10^5 particles/cm³. Moderate linear correlations were detected between on-road UFP concentrations and total traffic/HDDV with R²s of 0.24 and 0.31, respectively. The UFP I/O ratios in taxi cabs were not significantly different between freeways and local streets, but affected by the interventions (window positions and HECA filter availabilities) significantly. The speed didn't show apparent correlation with taxi I/O ratios either. The taxi vehicle mileages were moderately or highly correlated to their average I/O ratios with a R² of 0.56. The taxi vehicle make model was an important factor that affecting its I/O ratios. Using HECA filter can significantly reduce both the UFP concentrations and UFP I/O ratios in taxi cabs. The reduction would be more obvious if the drivers keep the windows closed.

In addition to the two specific aims, we (1) calculated the air exchange rates (AERs) in taxi cabin by using CO₂ as tracer gas, (2) collected and analyzed taxi drivers' urine samples twice a day to explore the biomarkers of UFP exposures, and (3) explored how the exposure to air pollutants impact taxi drivers' ambulatory blood pressure and heart rate variability. The AERs were generally high in taxi cabs, ranging from several to hundreds of air exchange per hour. The AERs were affected by vehicle models. Crown Victoria had the highest overall air exchange rates among all the five different vehicle models. Also air exchange rates were higher when driving on freeways than driving on local streets. The urinary biomarker analysis results showed 1- and 2-NAP, 1-PYR and 9-FLU levels in the taxi driver group were significantly higher than the control group. The possible factors affecting the 1-PYR levels could be driver age, years as driver, shift time, sampling time, creatinine levels, UPF levels and PM_{2.5} levels, based on the longitudinal model. The statistical data analysis on these HRV data is still an on-going process when this report is drafted. We plan to publish these data, analysis, and findings in peer-reviewed journals later.

REFERENCES

- Apte, M. G., W. J. Fisk, et al. (2000). "Associations between indoor CO₂ concentrations and sick building syndrome symptoms in US office buildings: An analysis of the 1994-1996 BASE study data." Indoor Air-International Journal of Indoor Air Quality and Climate **10**(4): 246-257.
- Baek, S. O., R. A. Field, et al. (1991). "A REVIEW OF ATMOSPHERIC POLYCYCLIC AROMATIC-HYDROCARBONS - SOURCES, FATE AND BEHAVIOR." Water Air and Soil Pollution **60**(3-4): 279-300.
- EPA, U. S. (2012, Sep 07, 2012). "Fuel Economy Database." Retrieved Sep 7, 2012, from <http://www.fueleconomy.gov/feg/download.shtml>.
- Ferin, J., G. Oberdorster, et al. (1990). "Increased Pulmonary Toxicity of Ultrafine Particles .1. Particle Clearance, Translocation, Morphology." Journal of Aerosol Science **21**(3): 381-384.
- Fletcher, B. and C. J. Saunders (1994). "Air change rates in stationary and moving motor-vehicles." Journal of Hazardous Materials **38**(2): 243-256.
- Frampton, M. W., J. C. Stewart, et al. (2006). "Inhalation of ultrafine particles alters blood leukocyte expression of adhesion molecules in humans." Environmental Health Perspectives **114**(1): 51-58.
- Fruin, S., D. Westerdahl, et al. (2008). "Measurements and Predictors of On-road Ultrafine Particle Concentrations and Associated Pollutants in Los Angeles." Atmospheric Environment **42**(2): 207-219.
- Fruin, S. A., N. Hudda, et al. (2011). "Predictive Model for Vehicle Air Exchange Rates Based on a Large, Representative Sample." Environmental Science & Technology **45**(8): 3569-3575.
- Fruin, S. A., N. Hudda, et al. (2011). "Predictive model for vehicle air exchange rates based on a large, representative sample." Environmental science & technology **45**(8): 3569-3575.
- Gilmour, P. S., A. Ziesenis, et al. (2004). "Pulmonary and systemic effects of short-term inhalation exposure to ultrafine carbon black particles." Toxicology and Applied Pharmacology **195**(1): 35-44.
- Goldstein, I. B., D. Shapiro, et al. (1999). "Ambulatory Blood Pressure, Heart Rate, and Neuroendocrine Responses in Women Nurses During Work and Off Work Days." Psychosomatic Medicine **61**(3): 387-396.
- Hansen, A. M., H. Wallin, et al. (2004). "Urinary 1-hydroxypyrene and mutagenicity in bus drivers and mail carriers exposed to urban air pollution in Denmark." Mutation Research-Genetic Toxicology and Environmental Mutagenesis **557**(1): 7-17.
- Harrison, R. M., D. J. T. Smith, et al. (1996). "Source apportionment of atmospheric polycyclic aromatic hydrocarbons collected from an urban location in Birmingham, UK." Environmental Science & Technology **30**(3): 825-832.
- Hitchins, J., L. Morawska, et al. (2000). "Concentrations of submicrometre particles from vehicle emissions near a major road." Atmospheric Environment **34**(1): 51-59.
- Hudda, N. and S. A. Fruin (2013). "Models for Predicting the Ratio of Particulate Pollutant Concentrations Inside Vehicles to Roadways." Environmental Science & Technology **47**(19): 11048-11055.
- Hudda, N., E. Kostenidou, et al. (2011). "Vehicle and driving characteristics that influence in-cabin particle number concentrations." Environmental science & technology **45**(20): 8691-8697.

- Jongeneelen, F. J. (2001). "Benchmark guideline for urinary 1-hydroxypyrene as biomarker of occupational exposure to polycyclic aromatic hydrocarbons." Annals of Occupational Hygiene **45**(1): 3-13.
- Knibbs, L. D., R. De Dear, et al. (2009). "Field study of air change and flow rate in six automobiles." Indoor air **19**(4): 303-313.
- Knibbs, L. D., R. J. de Dear, et al. (2009). "Field study of air change and flow rate in six automobiles." Indoor Air **19**(4): 303-313.
- Knibbs, L. D., R. J. de Dear, et al. (2009). "On-road ultrafine particle concentration in the M5 East road tunnel, Sydney, Australia." Atmospheric Environment **43**(22-23): 3510-3519.
- Kroll, A., J. K. Gietl, et al. (2013). "In vitro toxicology of ambient particulate matter: correlation of cellular effects with particle size and components." Environmental Toxicology **28**(2): 76-86.
- LA DOT (2010). "Analysis of taxicab driver compensation in Los Angeles."
- Lee, E. S., C.-C. D. Fung, et al. (2015). "Evaluation of a High Efficiency Cabin Air (HECA) Filtration System for Reducing Particulate Pollutants Inside School Buses." Environmental Science & Technology **49**(6): 3358-3365.
- Lee, E. S. and Y. Zhu (2014). "Application of a high-efficiency cabin air filter for simultaneous mitigation of ultrafine particle and carbon dioxide exposures inside passenger vehicles." Environmental Science & Technology **48**(4): 2328-2335.
- Lee, W.-J., Y.-F. Wang, et al. (1995). "PAH characteristics in the ambient air of traffic-source." Science of the Total Environment **159**(2-3): 185-200.
- Lee, W. J., Y. F. Wang, et al. (1995). "PAH CHARACTERISTICS IN THE AMBIENT AIR OF TRAFFIC-SOURCE." Science of the Total Environment **159**(2-3): 185-200.
- Li, N., C. Sioutas, et al. (2003). "Ultrafine Particulate Pollutants Induce Oxidative Stress and Mitochondrial Damage." Environmental Health Perspectives **111**(4): 455-460.
- Li, Z., L. Romanoff, et al. (2012). "Excretion Profiles and Half-Lives of Ten Urinary Polycyclic Aromatic Hydrocarbon Metabolites after Dietary Exposure." Chemical Research in Toxicology **25**(7): 1452-1461.
- MacKinnon, D. F., B. Craighead, et al. (2007). "Carbon dioxide provocation of anxiety and respiratory response in bipolar disorder." Journal of Affective Disorders **99**(1-3): 45-49.
- Marr, L. C., K. Dzepina, et al. (2006). "Sources and transformations of particle-bound polycyclic aromatic hydrocarbons in Mexico City." Atmospheric Chemistry and Physics **6**: 1733-1745.
- McArdle, W. D., F. I. Katch, et al. (2010). Exercise Physiology: Nutrition, Energy, and Human Performance, Lippincott Williams & Wilkins.
- Morawska, L., Z. Ristovski, et al. (2008). "Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure." Atmospheric Environment **42**(35): 8113-8138.
- Oberdorster, G. (2001). "Pulmonary effects of inhaled ultrafine particles." International Archives of Occupational and Environmental Health **74**(1): 1-8.
- Oberdorster, G., J. Ferin, et al. (1990). "Increased Pulmonary Toxicity of Ultrafine Particles .2. Lung Lavage Studies." Journal of Aerosol Science **21**(3): 384-387.
- Ott, W. R. and H. C. Siegmann (2006). "Using multiple continuous fine particle monitors to characterize tobacco, incense, candle, cooking, wood burning, and vehicular sources in indoor, outdoor, and in-transit settings." Atmospheric Environment **40**(5): 821-843.
- Panasevich, S., K. Leander, et al. (2013). "Interaction between air pollution exposure and genes in relation to levels of inflammatory markers and risk of myocardial infarction." Bmi Open **3**(9).

- Park, J. H., J. D. Spengler, et al. (1998). "Measurement of air exchange rate of stationary vehicles and estimation of in-vehicle exposure." Journal of Exposure Analysis and Environmental Epidemiology **8**(1): 65-78.
- Peters, A., S. von Klot, et al. (2004). "Exposure to traffic and the onset of myocardial infarction." New England Journal of Medicine **351**(17): 1721-1730.
- Pope, C. A. and D. W. Dockery (2006). "Health Effects of Fine Particulate Air Pollution: Lines That Connect." Journal of the Air & Waste Management Association **56**(6): 709-742.
- Pope, C. A., D. W. Dockery, et al. (1995). "Review of epidemiological evidence of health-effects of particulate air pollution." Inhalation Toxicology **7**(1): 1-18.
- Qi, C., N. Stanley, et al. (2008). "Laboratory and on-road evaluations of cabin air filters using number and surface area concentration monitors." Environmental Science & Technology **42**(11): 4128-4132.
- Satish, U., M. J. Mendell, et al. (2012). "Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance." Environmental Health Perspectives **120**(12): 1671-1677.
- Schnall, P. L., J. E. Schwartz, et al. (1998). "A Longitudinal Study of Job Strain and Ambulatory Blood Pressure: Results From a Three-Year Follow-up." Psychosomatic Medicine **60**(6): 697-706.
- Somers, C. M., B. E. McCarry, et al. (2004). "Reduction of particulate air pollution lowers the risk of heritable mutations in mice." Science **304**(5673): 1008-1010.
- Strak, M., N. A. H. Janssen, et al. (2012). "Respiratory health effects of airborne particulate matter: the role of particle size, composition, and oxidative potential-the RAPTES project." Environmental Health Perspectives **120**(8): 1183-1189.
- Tainio, M., J. T. Tuomisto, et al. (2005). "Health effects caused by primary fine particulate matter (PM2.5) emitted from buses in the Helsinki metropolitan area, Finland." Risk Analysis **25**(1): 151-160.
- Vione, D., S. Barra, et al. (2004). "Polycyclic aromatic hydrocarbons in the atmosphere: monitoring, sources, sinks and fate. II: Sinks and fate." Annali Di Chimica **94**(4): 257-268.
- Weichenthal, S. A., K. Godri-Pollitt, et al. (2013). "PM2.5, oxidant defence and cardiorespiratory health: a review." Environmental Health **12**.
- Xu, B., S. S. Liu, et al. (2011). "Effects of vehicle cabin filter efficiency on ultrafine particle concentration ratios measured in-cabin and on-roadway." Aerosol Science and Technology **45**(2): 234-243.
- Xu, B. and Y. F. Zhu (2009). "Quantitative Analysis of the Parameters Affecting In-Cabin to On-Roadway (I/O) Ultrafine Particle Concentration Ratios." Aerosol Science and Technology **43**(5): 400-410.
- Xue, W. L. and D. Warshawsky (2005). "Metabolic activation of polycyclic and heterocyclic aromatic hydrocarbons and DNA damage: A review." Toxicology and Applied Pharmacology **206**(1): 73-93.
- Zhu, Y. F., A. Eiguren-Fernandez, et al. (2007). "In-cabin commuter exposure to ultrafine particles on Los Angeles freeways." Environmental Science & Technology **41**(7): 2138-2145.

LIST OF PUBLICATIONS

Shi Shu, Nu Yu, Yueyan Wang, and Yifang Zhu, Measuring and modeling air exchange rates inside taxi cabs in Los Angeles, California, submitted to *Atmospheric Environment*

Shi Shu, Nu Yu, BongKyoo Choi, Yifang Zhu, Impacts of occupational exposure to particles on heart rate variability of Los Angeles taxi drivers. Manuscript in preparation.

Nu Yu, Shi Shu, and Yifang Zhu, Assessing taxi vehicle in-cabin PM levels and in-cabin versus on-road ratios. Manuscript in preparation.

Nu Yu, Shi Shu, Yan Lin, and Yifang Zhu, Analysis of Los Angeles taxi drivers' urinary PAH metabolites and their associations with occupational exposure to traffic pollutants. Manuscript in preparation.

Cumulative Inclusion Enrollment Report

This report format should NOT be used for collecting data from study participants.

Study Title: Assessing and Reducing Taxi Drivers' Exposure to Ultrafine Particles

Comments:

Racial Categories	Ethnic Categories									Total
	Not Hispanic or Latino			Hispanic or Latino			Unknown/Not Reported Ethnicity			
	Female	Male	Unknown/ Not Reported	Female	Male	Unknown/ Not Reported	Female	Male	Unknown/ Not Reported	
American Indian/ Alaska Native	0	0	0	0	0	0	0	0	0	0
Asian	0	7	0	0	0	0	0	0	0	7
Native Hawaiian or Other Pacific Islander	0	0	0	0	0	0	0	0	0	0
Black or African American	0	4	0	0	0	0	0	0	0	4
White	0	6	0	0	0	0	0	0	0	6
More Than One Race	0	0	0	0	0	0	0	0	0	0
Unknown or Not Reported	0	0	0	0	0	0	1	4	0	5
Total	0	17	0	0	0	0	1	4	0	22