

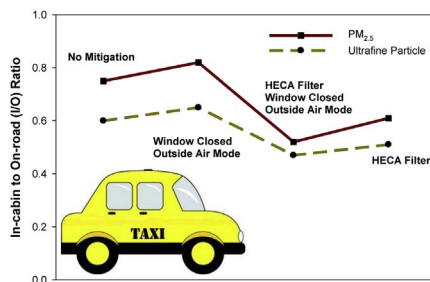
# Assessing and reducing fine and ultrafine particles inside Los Angeles taxis

Nu Yu, Shi Shu, Yan Lin, Yifang Zhu\*

Department of Environmental Health Sciences, Jonathan and Karin Fielding School of Public Health, University of California Los Angeles, CA 90095, United States



## GRAPHICAL ABSTRACT



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## ABSTRACT

Taxi drivers and passengers are exposed to high levels of traffic-related air pollutants, but their exposures to fine (PM<sub>2.5</sub>) and ultrafine particles (UFPs) and related mitigation strategies are rarely explored. In this study, UFP and PM<sub>2.5</sub> concentrations were monitored concurrently inside and outside of 22 taxis under different ventilation and mitigation conditions. Under realistic working conditions (no mitigation; NM), the average UFP and PM<sub>2.5</sub> levels inside taxis were  $1.46 \times 10^4$  particles/cm<sup>3</sup> and 26 µg/m<sup>3</sup>, respectively. When the taxi ventilation was set to outside air mode and the windows kept closed, in-cabin UFP and PM<sub>2.5</sub> concentrations are significantly associated with on-road concentrations, driving speed, and cabin air filter usage. The average in-cabin to on-roadway (I/O) ratios for UFP and PM<sub>2.5</sub> were reduced from 0.60 to 0.75 under NM, to 0.47 and 0.52 under the most stringent mitigation strategy of keeping the windows closed and operating a high efficiency cabin air filter (WC + HECA). Among all tested taxi models, Toyota Prius exhibited the lowest UFP and PM<sub>2.5</sub> I/O ratios under WC + HECA. Switching cabin air filters from the originally equipped manufacturer filter (OEM) to a HECA filter reduced the UFP and PM<sub>2.5</sub> I/O ratios most effectively in Toyota Prius taxis as well.

## 1. Introduction

High concentrations of particulate matter (PM), such as fine (PM<sub>2.5</sub>, aerodynamic diameter ≤ 2.5 µm) and ultrafine particles (UFPs, diameter ≤ 100 nm), are usually observed on and near roadways (Zhu, 2012; Fruin et al., 2008; Zhu et al., 2007). PM has been shown to induce oxidative stress, mitochondria damage, and acute pulmonary inflammation (Kroll et al., 2013; Strak et al., 2012; Li et al., 2003). Previous studies have also reported an association between PM exposure

and cardiorespiratory diseases as well as increased morbidity and mortality (Pope and Dockery, 2006; Panasevich et al., 2013; Peters et al., 2004). The International Agency for Research on Cancer (IARC) Working Group unanimously classified outdoor air pollution and PM as carcinogenic to human (IARC Group 1) (World Health Organization, 2016).

Exposures to traffic emitted PM are of special concern for certain subpopulations, such as taxi drivers who spend more time in traffic than the general population. A report from the Los Angeles Department of

\* Corresponding author. 51-295B CHS, Department of Environmental Health Sciences, Jonathan and Karin Fielding School of Public Health, University of California Los Angeles, Los Angeles, CA 90095-1772, United States.

E-mail address: [yifang@ucla.edu](mailto:yifang@ucla.edu) (Y. Zhu).

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Transportation showed that there were more than 4000 taxi drivers working in Los Angeles (DOT, 2010). The daily exposures of taxi drivers to traffic emitted PM are likely to be much higher than people in other occupations, given their long work hours and the highly congested Los Angeles roadways (Lomax et al., 2013; Blasi and Leavitt, 2010).

Previous studies have shown that in-cabin UFP levels are usually lower than on-road levels because of the different mechanisms of particle loss (Xu and Zhu, 2009). In fact, both on-road concentrations and the in-cabin to on-road (I/O) ratios determine in-cabin exposures. Research studies conducted on regular passenger vehicles with windows closed reported that for traffic related PM, the I/O ratios were 0–0.4 when the vehicle ventilation was under in-cabin recirculation mode, and increased to 0.6–1.0 under outside air mode (Hudda and Fruin, 2013). However, there is a knowledge gap on UFP and PM<sub>2.5</sub> levels inside taxis and related I/O ratios, which is essential for understanding the taxi vehicle protection against traffic related PM and estimating taxi driver and passenger exposures.

Previous studies have found that the significant determinants of UFP I/O ratios in passenger vehicles include ventilation modes, driving speed, cabin filtration performance, surface deposition, and penetration factor (Zhu et al., 2007; Xu and Zhu, 2009). Vehicle model and car age and mileage were also important (Xu and Zhu, 2009; Shu et al., 2015). How these factors may influence taxi vehicles, which have limited vehicle models but higher mileage than regular passenger vehicles, is poorly understood. Setting the vehicle ventilation to outside air mode and improving cabin filter efficiency is a promising mitigation strategy to reduce in-cabin UFP and PM<sub>2.5</sub> and avoid in-cabin carbon dioxide (CO<sub>2</sub>) accumulation. Our previous studies showed that the High Efficiency Cabin Air (HECA) filters reduced the in-cabin UFPs and PM<sub>2.5</sub> concentrations in passenger vehicles and school buses significantly under outside air mode when windows were kept closed (Lee and Zhu, 2014; Lee et al., 2015). However, taxi vehicles were found to be more frequently used than passenger vehicles with higher air exchange rates (AERs) (Shu et al., 2015). Thus, the effectiveness of these mitigation strategies in reducing PM inside taxis needs to be evaluated.

This study aims to (1) measure UFP and PM<sub>2.5</sub> levels concurrently inside and outside of taxis, (2) identify factors affecting the in-cabin UFP and PM<sub>2.5</sub> levels and their I/O ratios, and (3) evaluate the effectiveness of various exposure mitigation strategies for taxis.

## 2. Materials and methods

### 2.1. Taxi recruitment

The detailed recruitment procedure has been described in a previous study (Shu et al., 2015). Briefly, because taxi drivers make at least twice as much on the one in five days that they are permitted to pick up fares at the Los Angeles International Airport (LAX), virtually every registered taxi driver in Los Angeles passes through the LAX taxi holding lot during that permitted day. The recruitment campaign was conducted at the LAX taxi holding lot for five consecutive days on February 12 to 16, 2013, and a short recruitment form was designed and handed out to the taxi drivers. A total of 2449 recruitment forms were handed out, and 316 complete forms were collected, yielding a response rate of 13%. Out of these 316 taxi drivers, 121 who indicated never smoking cigarettes were eligible to participate in the study. Finally, 22 taxi drivers were selected randomly from the 121 eligible drivers stratified by their age and vehicle make/model. Information about their taxis is summarized in Table 1. The UCLA Institutional Review Board (IRB) approved the study design and experimental protocol in 2012. Informed consent was obtained from all participating taxi drivers.

### 2.2. Ventilation and mitigation conditions

The HECA filters were provided by an industrial partner, and

**Table 1**  
Summary of the tested taxi models and specifications.

Taxi Type	Maker	Model	N	Model Year	Average Mileage (mile) (SD)	Cabin Volume (m <sup>3</sup> )
Hatchback	Toyota	Prius	10	2005–2012	114,000 (39,000)	3.3
Sedan	Ford	Crown Victoria	5	2005–2008	277,000 (93,000)	3.8
	Toyota	Camry	3	2009–2012	118,000 (46,000)	3.3
Minivan	Chevy	Uplander	1	2005	269,000	8.1
	Dodge	Grand Caravan	3	2007–2012	176,000 (82,000)	8.8

installed into the taxi cabin filter holders by researchers. These HECA filters were similar to originally equipped manufacturer (OEM) cabin air filters with respect to size, shape, and structure (i.e., the pleated panel type) but with different filtration media. The OEM filters were typically composed of a single layer of glass fibers, whereas the HECA filters were manufactured in double layer, with synthetic fibers on the upstream side and glass fibers on the downstream side, which achieved significantly higher filtration efficiencies. The HECA filter manufacturer claimed that the filtration efficiency is equivalent to a minimum efficiency reporting value (MERV) rating of 16. The specifications and the scanning electron microscope (SEM) images of the HECA filter were reported elsewhere (Lee and Zhu, 2014). Unlike other taxi models with OEM cabin air filter holders behind or inside the glove boxes, Ford Crown Victoria taxis do not have cabin air filter holders. Since the portable High Efficiency Particulate Air (HEPA) purifiers have been reported to be effective in reducing in-cabin particle levels (Tartakovsky et al., 2013; Zhang and Zhu, 2011), a portable HEPA purifier (Model CWH3002, Honeywell Inc., Morris Plains, NJ) was used in those Ford crown Victoria taxis instead. The air purifier had a built-in fan drawing air through a HEPA filter with a clean air delivery rate (CADR) of 25 m<sup>3</sup> hour<sup>-1</sup>. During the sampling tests, the portable air purifier was placed in the rear of the cabin.

The experiments were designed to test various combinations of ventilation settings, window positions, and filter usages. In total, four conditions were tested for each taxi: (1) no mitigation (NM), to simulate the realistic working conditions in which the ventilation/window was not controlled, with the OEM filter or no filter in use; (2) ventilation set to outside air to avoid CO<sub>2</sub> accumulation, and windows were closed, with the OEM filter or no filter in use (WC); (3) the ventilation was set to outside air to avoid CO<sub>2</sub> accumulation, and windows were closed with the HECA filter in use (WC + HECA), which is considered the most stringent mitigation strategy in this study; and (4) the ventilation and windows were not controlled, but the HECA filter was in use (HECA), which simulates realistic driving but uses the HECA filter as a simple engineering control. Every taxi was tested for four consecutive days under one of the four conditions on each day.

### 2.3. Driving routes

On each test day, the driver drove approximately six hours in the Greater Los Angeles area as he would typically do in his everyday work. A researcher rode along in the taxi to operate all sampling instruments. On the first test day, each taxi driver was asked to drive from the start location (University of California Los Angeles) to the area where he usually worked and then repeat what he did in his previous work day. The testing routes included local streets, arterial roads, and freeways in the Greater Los Angeles Area (Shu et al., 2015). The start time of each test day and the driving routes were similar to minimize the differences in traffic and meteorological conditions for each individual taxi and driver. In total, field measurements were conducted on 83 different days from April 29 to November 7, 2013. Five test days were lost

because two taxi drivers only partially completed their four-day tests. Approximately 500 h of data were collected from 11,000 km of driving.

#### 2.4. Field measurements

In-cabin and on-road PM<sub>2.5</sub> and UFP concentrations were concurrently monitored inside and outside of each taxi. Two identical sets of direct reading instruments were deployed for the measurements. One set monitored the in-cabin levels with tubing extending to the breathing zone of the driver. The other set monitored on-road concentrations with tubing extending outside through the back seat window. Three mm (id) polyurethane (PUR) tubing of the same length was used for both in-cabin and on-road sampling to ensure the same level of diffusion loss if any. The on-road air sampling tubing was mounted onto the window. The window gaps were then sealed similar to what we did previously for passenger vehicles (Lee and Zhu, 2014). All tests were conducted with one driver and one researcher in the taxi.

Portable condensation particle counters (CPCs, Model 3007, TSI Inc., St. Paul, MN) were deployed to measure the UFP in a size range of 0.01 to greater than 1.0 μm. DustTrak monitors (Model 8520, TSI Inc., St. Paul, MN) with PM<sub>2.5</sub> impactors installed at the inlets were used to measure PM<sub>2.5</sub> mass concentrations. The driving routes and speeds were recorded by a GPS unit (Qstarz GPS BT-1000XT, Taipei, Taiwan).

Temperature, relative humidity, carbon monoxide (CO), and CO<sub>2</sub> concentrations were measured simultaneously inside and outside of each taxi with two TSI Indoor Air Quality monitors (Q-Trak Plus, Model 8554, TSI Inc., St. Paul, MN). As both the in-cabin CO<sub>2</sub> emission rate due to human exhalation and the cabin volume are known, the AER can be estimated using CO<sub>2</sub> as a tracer gas. The detailed method for AER calculation and results have been presented in another study (Shu et al., 2015).

#### 2.5. Data collection, analysis, and quality assurance

CPCs and DustTraks were zero calibrated prior to the field sampling and set to a logging interval of one second. DustTraks use a light scattering method to determine PM<sub>2.5</sub> mass concentration in real-time, which usually generates higher results than gravimetric methods. Hence the DustTraks were calibrated against simultaneous gravimetric measurements of PM<sub>2.5</sub> using a TEOM<sup>®</sup> (Series 1400A, Thermo Scientific Co., Waltham, MA). Since a factor of 2.4 was achieved for data correction, all DustTrak readings were divided by 2.4 before analysis. The same correction factor was used in previous studies for PM<sub>2.5</sub> measurement correction (Yanosky et al., 2002; Zhang and Zhu, 2010). Each pair of instruments was collocated before and after the field sampling for data quality assurance. Good correlations with little bias were observed for both UFP and PM<sub>2.5</sub> with less than 5% of error and R (Fruin et al., 2008) greater than 0.95.

The collected data were thoroughly checked, and unrealistic data points were removed, such as UFP readings that remained unchanged for more than a minute, which were usually due to low isopropanol levels or the instrument was tilted. Negative or zero PM<sub>2.5</sub> and UFP readings that were generated when the built-in pumps were blocked were also removed. Approximately 85% of the collected data were used for further analysis. Because PM measurements at the adjacent time points were highly correlated, one-second readings were averaged to five-minute averages before further analysis. The I/O ratios were calculated from the five minute average in-cabin PM concentrations divided by the five minute average on-road concentrations. Other methods were also explored, such as using linear regression coefficients of in-cabin concentrations vs. on-road concentrations to calculate the average I/O ratios, and yielded similar results.

SAS 9.4 software (SAS Institute, Cary, NC) was used for statistical analysis. Student's *t*-tests or paired *t*-tests were used for two groups of data comparison. Analysis of variances (ANOVA) was used to compare multiple groups of data. The mixed effects linear regression method was

used to evaluate variable associations. The mixed effect model used in this study can be expressed by the following equation:

$$\begin{aligned} \log(\text{in} - \text{cabin level})_{ij} = & \alpha + (\text{taxi vehicle})_i + \beta_1 \log(\text{on} - \text{road level})_{ij} \\ & + \beta_2(\text{vehicle mileage})_{ij} + \beta_3(\text{vehicle age})_{ij} \\ & + \beta_4(\text{mitigation})_{ij} + \beta_5(\text{driving speed})_{ij} \\ & + \beta_6(\text{car model})_{ij} + \varepsilon_{ij} \end{aligned} \quad (1)$$

Where *i* is the index of each taxi vehicle or driver, *j* is the index of the calculated 5-min average in-cabin, on-road concentrations or driving speed,  $\alpha$  is the general mean,  $(\text{taxi vehicle})_i$  is the random intercept of each vehicle, the  $\beta'_s$  are the fixed slopes of each factors respectively, and  $\varepsilon_{ij}$  is the residual.

Before conducting any statistical analysis (e.g., the regression analysis, *t*-tests, and ANOVA), PM<sub>2.5</sub> and UFP concentrations and calculated I/O ratios were log transformed to achieve normal distributions (Shapiro-Wilk test *p* > 0.05). The level of significance was set as *p* < 0.05.

### 3. Results and discussion

#### 3.1. Recruitment survey

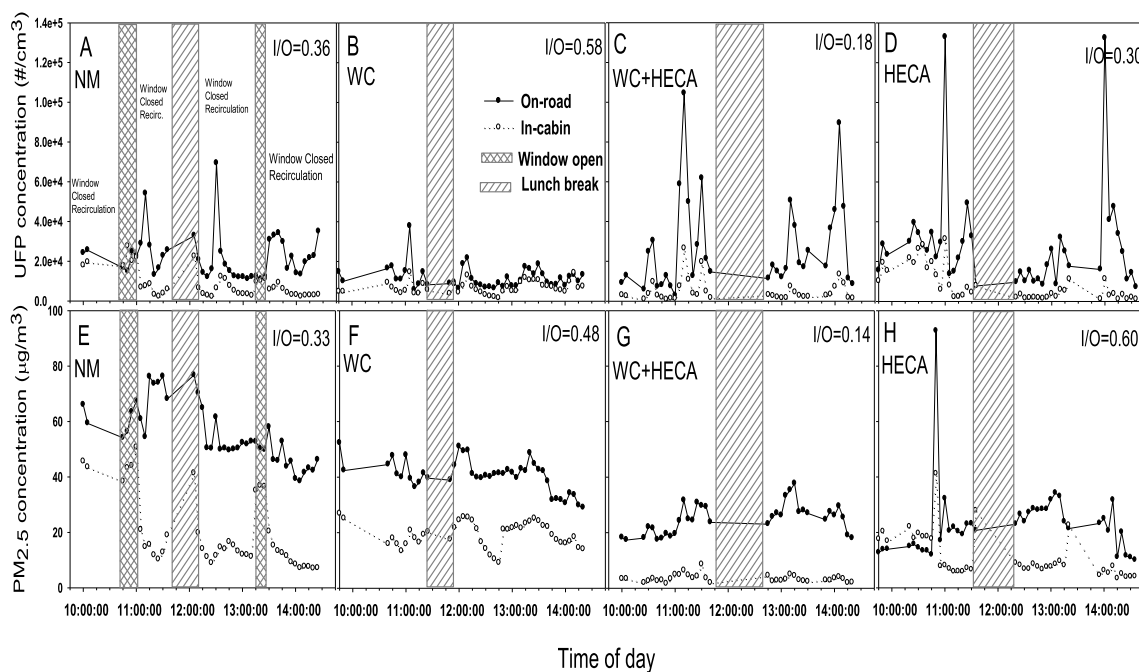
Table S1 summarizes the taxi driver information collected from the 316 recruitment forms that were returned. It shows that Ford Crown Victoria (32.6%) and Toyota Prius (26.6%) were the most common models for taxi vehicles. Other vehicle models include Dodge Caravan (13.0%), Toyota Camry (7.8%), Chrysler Town & County (3.5%), Chevy Uplander (1.6%), and others (14.9%). The five vehicle models tested in this study (Toyota Prius, Ford Crown Victoria, Toyota Camry, Dodge Caravan, and Chevy Uplander) comprised of 81.6% of all types of taxi vehicle models in Los Angeles. Surveyed taxi model years ranged from 1987 to 2012, and 55.7% of the vehicles were more than 5 years old.

The survey results also show that these taxi drivers worked a mean of 11.9 (SD 2.3) hours a day and 6.1 (SD 0.1) days a week for 9.8 (SD 8.3) years. They spent 4.2 (SD 2.6) hours on freeways on each work day, and the taxi windows were open for 76.1% (SD 12.4%) of their driving time (Table S1).

#### 3.2. Typical on-road and in-cabin PM concentrations

Since the UFP and PM<sub>2.5</sub> data were collected from moving taxis, the results reflect both temporal and spatial variations. Peaks were usually observed when the taxis were driving on freeways during traffic rush hours or adjacent to high emitters such as heavy duty trucks. Fig. 1 shows the typical time series of on-road and in-cabin UFP and PM<sub>2.5</sub> concentrations simultaneously collected with a Toyota Prius taxi. The four tested conditions were marked on different sections of Fig. 1. Rapid fluctuations were observed for both on-road UFP and PM<sub>2.5</sub> concentrations and the UFP levels changed faster and more substantially than PM<sub>2.5</sub>. Comparing the patterns among different conditions, most of the concentration peaks occurred at a similar time of the day. Because the experiment was designed to have the same start time and driving routes for each taxi driver to minimize the influences from traffic and meteorological changes, the spikes reflect the high concentrations at fixed times of the day and locations. Although the same driving route and sampling time were used for each of the four test days, the on-road PM<sub>2.5</sub> were still significantly different by ANOVA (*p* < 0.05) (Table 2). Thus, the data analysis described below focused on the in-cabin to on-road (I/O) ratios rather than absolute in-cabin levels.

The simultaneously collected on-road and in-cabin PM levels also have similar temporal patterns. As shown in Fig. 1A and E under the NM condition, when the taxi driver took short breaks, parked the taxi and opened the window at approximately 10:45–11:00 and 13:15–13:30, for example, the in-cabin UFP concentrations fluctuated



**Fig. 1.** Time series of UFP and PM<sub>2.5</sub> on-road and in-cabin concentrations under four test conditions for a Toyota Prius taxi. Solid lines show on-road (outside taxi cabin) concentrations and dotted lines show in-cabin concentrations. NM indicates “no mitigation”, WC indicates “window closed using outside air mode”, and HECA indicates “high efficiency cabin air filter in use”. The average I/O ratios under each condition were calculated and marked on the figures. The crosshatched areas indicate times when the drivers took short breaks and briefly parked their taxis.

less and were similar to the outside levels (crosshatched areas on Fig. 1A and E). However, when the ventilation was set at recirculation mode and window closed (WC + RC), the in-cabin concentrations were substantially lower than on-road levels. Similar effects of recirculation

have been reported for passenger vehicles (Zhu et al., 2007; Hudda et al., 2012). Under the WC + HECA condition, UFP and PM<sub>2.5</sub> levels inside taxis were consistently lower than on-road levels (Fig. 1C and G). Notably, under the WC condition, since the ventilation set to outside air

**Table 2**  
Summary of on-road and in-cabin PM concentrations and I/O ratios.

Interventions	Mean (IQR <sup>a</sup> )			ANOVA <sup>b</sup>			p-value*
	NM <sup>c</sup>			WC <sup>d</sup>	WC <sup>d</sup> + HECA <sup>e</sup>	HECA	
	Overall NM	NM-RC + WC <sup>f</sup>	NM-not RC + WC <sup>g</sup>				
<b>UFP</b>							
On-road concentration (x10 <sup>4</sup> particles/cm <sup>3</sup> )	2.57 (1.28, 3.34)	2.44 (1.25, 3.13)	2.61 (1.27, 3.37)	2.73 (1.35, 3.62)	2.69 (1.24, 3.64)	2.81 (1.53, 3.68)	0.09
In-cabin concentration (particles/cm <sup>3</sup> )	1.46 (0.46, 1.87)	0.73 (0.24, 0.72)	1.72 (0.66, 2.22)	1.76 (0.77, 2.24)	1.13 (0.39, 1.44)	1.47 (0.44, 2.08)	< 0.01
Reduction (%)	40 (14, 74)	67 (64, 87)	29 (11, 50)	35 (25, 56)	53 (36, 78)	49 (20, 81)	< 0.01
I/O ratio	0.60(0.26, 0.86)	0.33 (0.14, 0.36)	0.71 (0.50, 0.89)	0.65 (0.55, 0.76)	0.47 (0.22, 0.80)	0.51 (0.19, 0.80)	< 0.01
<b>PM<sub>2.5</sub></b>							
On-road concentration (µg/m <sup>3</sup> )	35 (16, 43)	31 (17, 42)	35 (15, 40)	30 (17, 33)	30 (20, 34)	34 (22, 42)	< 0.01
In-cabin concentration (µg/m <sup>3</sup> )	26 (14, 27)	15 (10, 18)	28 (15, 27)	20 (13.27, 22.93)	14 (9.72, 14.78)	20 (12, 25)	< 0.01
Reduction <sup>h</sup> (%)	25 (5, 43)	42 (28, 63)	21 (2, 37)	34 (2, 37)	48 (37, 65)	39 (21, 60)	< 0.01
I/O ratio <sup>i</sup>	0.75 (0.57, 0.95)	0.58 (0.37, 0.72)	0.79 (0.63, 0.98)	0.82 (0.63, 0.98)	0.52 (0.36, 0.63)	0.61 (0.40, 0.79)	< 0.01

\*The level of significance was set as p < 0.05.

<sup>a</sup> IQR: interquartile range.

<sup>b</sup> ANOVA: analysis of variances among overall NM, WC, WC + HECA and HECA. P-values reflects the significances of the differences among intervention groups.

<sup>c</sup> NM: no mitigation. taxi window and ventilation not under control.

<sup>d</sup> WC: taxi window all closed with outside air ventilation mode.

<sup>e</sup> HECA: high efficiency cabin air filter or high efficiency particulate air purifier in use.

<sup>f</sup> NM-RC + WC: no mitigation, taxi ventilation set to recirculation mode with window closed.

<sup>g</sup> NM-not RC + WC: no mitigation, but not under NM-RC + WC.

<sup>h</sup> Concentration reduction from on-road to in-cabin.

<sup>i</sup> In-cabin vs. on-road concentration ratio.

mode with OEM filter in use, the in-cabin UFP levels were closer to on-road levels, which lead to a higher average I/O ratio than that measured under the NM condition which was mainly in recirculation mode for this particular taxi (Fig. 1A and B). Fig. 1C and G shows that under the WC + HECA condition and when the ventilation was set to outside air, the in-cabin UFP and PM<sub>2.5</sub> concentrations were still following the on-road trend, but the levels were much lower. This indicates that the HECA filter reduced both UFP and PM<sub>2.5</sub> levels inside this taxi and lowered their I/O ratios. Fig. 1C and D, 1G and 1H show similar UFP and PM<sub>2.5</sub> I/O ratios between WC + HECA and HECA. The reason for this similarity is when testing WC and WC + HECA on the 2nd and 3rd test days, the driver was told to keep the windows closed and set the ventilation to outside air mode. Consequently, on the 4th test day (HECA condition), the driver tended to close the windows and set the ventilation to outside mode although he was allowed to set the ventilation and window position as he preferred.

### 3.3. Effects of ventilation and mitigation strategy on PM levels and I/O ratios

Table 2 summarizes the on-road and in-cabin UFP and PM<sub>2.5</sub> concentrations and their I/O ratios under four ventilation and mitigation conditions. Since the simultaneous rapid CO<sub>2</sub> build-up and UFP exponential decay indicate the vehicle uses the recirculation mode when the windows are closed (Zhu et al., 2007), the window closed with recirculation mode (RC + WC) condition was identified for all of the NM tests. It shows that throughout the study, the average on-road UFP concentrations ranged from  $2.57 \times 10^4$  to  $2.81 \times 10^4$  particles/cm<sup>3</sup> and the average on-road PM<sub>2.5</sub> concentrations ranged from 30 to 35 µg/m<sup>3</sup>. The average in-cabin UFP and PM<sub>2.5</sub> concentrations under NM which simulates the realistic working conditions without any mitigation, were  $1.46 \times 10^4$  particles/cm<sup>3</sup> and 26 µg/m<sup>3</sup>, respectively. These levels were approximately 40% and 25% lower than the on-road levels, with corresponding I/O ratios of 0.60 and 0.75.

ANOVA and *t*-test results showed that in-cabin UFP and PM<sub>2.5</sub> I/O ratios under the four different conditions were significantly different ( $p < 0.05$ ). When the ventilation was set to outside air mode under the WC + HECA condition, the average in-cabin UFP and PM<sub>2.5</sub> concentrations were approximately 53% and 48% lower than the on-road levels, with corresponding I/O ratios of 0.47 and 0.52, respectively. Compared with the other three conditions, WC + HECA resulted in the lowest I/O ratios. The highest average I/O ratios were found under WC condition. This is because under NM, the ventilation was controlled by the driver. The ventilation was set to recirculation mode and the windows were kept closed for approximately 20% of the NM testing time. This made the I/O ratios lower under NM than under the WC condition, which always set to outside air mode.

The American Conference of Governmental Industrial Hygienists (ACGIH) has a 5000-ppm threshold limit value (TLV) for the 8-h time weighted average (TWA) exposure of CO<sub>2</sub>. The California Occupational Safety and Health Administration (Cal-OSHA) also has an 8-hour permissible exposure limit (PEL) of 5000-ppm for CO<sub>2</sub>. Exposure to CO<sub>2</sub> higher than 2500 ppm can significantly reduce decision making performances (Satish et al., 2012). Rapid in-cabin CO<sub>2</sub> accumulation has been observed in our previous studies when the vehicle ventilation was under recirculation mode (Zhu et al., 2007; Lee and Zhu, 2014).

The average on-road and in-cabin CO<sub>2</sub> concentrations and inter-quartile ranges under different driving conditions are summarized in Table S3. In general, the on-road CO<sub>2</sub> concentrations are in the similar ranges, but the in-cabin levels under four driving conditions show significant difference by ANOVA ( $p < 0.05$ ). Higher in-cabin CO<sub>2</sub> concentrations were observed under NM and HECA, when the recirculation mode was allowed. An average of 1220 ppm was found under the NM condition in this study (Table S3), and the maximum CO<sub>2</sub> level (4848 ppm) was observed under RC + WC. When the ventilation was set to outside air only, the other two driving conditions, WC and

WC + HECA, generated relatively lower average in-cabin CO<sub>2</sub> concentrations of 809 and 860 ppm, respectively (Table S3). Therefore, although the recirculation mode offers comparable or even lower PM I/O ratios than the outside air mode with WC + HECA (Table 2), the CO<sub>2</sub> accumulation makes the recirculation mode not a feasible in-cabin exposure mitigation strategy.

Compared with NM, the average UFP I/O ratio decreased from 0.60 to 0.51, and the average PM<sub>2.5</sub> I/O ratio decreased from 0.75 to 0.61 under the HECA condition. It should be noted, both NM and HECA allow the taxi drivers to have full control of the ventilation settings and window positions. Compared with WC, the average UFP I/O ratio decreased from 0.65 to 0.47, and the average PM<sub>2.5</sub> I/O ratio decreased from 0.82 to 0.52 under the WC + HECA condition. These results indicate that the HECA filter further reduced the UFP and PM<sub>2.5</sub> I/O ratios by 0.18 and 0.30 respectively, when windows were kept closed using outside air ventilation mode. These I/O ratio reductions are about twice as much as those when ventilation and window were not controlled (i.e., 0.09 for UFP and 0.14 for PM<sub>2.5</sub> between NM and HECA conditions).

### 3.4. Effects of car model

Fig. 2 summarizes the effects of taxi vehicle model on UFP and PM<sub>2.5</sub> I/O ratios under different test conditions. It shows that, under NM, Toyota Prius has the lowest average UFP I/O ratio among all models, and Toyota Camry has the lowest average PM<sub>2.5</sub> I/O ratio among the four taxi models (no data for Chevy Uplander due to instrument malfunction). The average UFP and PM<sub>2.5</sub> I/O ratios in Toyota Prius under WC (windows closed and ventilation set to outside air mode) increased when compared to NM (Fig. 2), indicating that simply closing vehicle windows and using outside air ventilation mode is not an effective mitigation strategy for Toyota Prius taxis. Under both WC + HECA and HECA conditions, the Toyota Prius has the lowest average I/O ratios for both UFP and PM<sub>2.5</sub> among all taxi models, indicating HECA filters work most effectively in Prius taxis.

Unlike other taxi models, the I/O ratios of Ford Crown Victoria under the four conditions were not significantly different by ANOVA (Fig. 2), suggesting that the portable air purifier had limited effects on I/O ratios in Ford Crown Victoria taxis. This is likely because the Ford Crown Victoria taxis were obtained from retired police cars with the oldest car age, highest mileage, and greatest wear and tear. The average AER of the Ford Crown Victoria taxis was 75 h<sup>-1</sup>, which is also much higher than the average AERs of the other tested taxi models which range from 19 to 37 h<sup>-1</sup> (Shu et al., 2015). The higher AER in the Ford Crown Victoria could make the portable air purifier less efficient than the HECA filters used in other taxi models.

Previous studies have shown that using a portable HEPA purifier could reduce UFP levels by 95–99% in passenger vehicles (Tartakovsky et al., 2013) and up to 50% of the total particles in school buses (Zhang and Zhu, 2011). However, our results showed that the efficiency of the air purifier was negligible in Ford Crown Victoria taxis. The portable air purifier used in this study operates at a CADR of 25 m<sup>3</sup> h<sup>-1</sup>, while the average AER of tested Ford Crown Victoria taxis was 75 h<sup>-1</sup> (Shu et al., 2015). The estimated volume of the Ford Crown Victoria taxis cabin is 3.8 m<sup>3</sup> (Table 1), and the total volume of in-cabin air being exchanged was 75 h<sup>-1</sup> × 3.8 m<sup>3</sup> = 284 m<sup>3</sup> h<sup>-1</sup>. This is approximately 11.4 times the CADR of the portable air purifier, making its effect negligible. In contrast, Tartakovsky and colleagues used an air purifier with a higher CADR of 30 m<sup>3</sup> h<sup>-1</sup> and smaller vehicle cabin volumes between 2.0 and 2.5 m<sup>3</sup>, which may help explain the higher efficiency observed in their study (Tartakovsky et al., 2013).

Among all the tested taxi models, Toyota Prius had the highest I/O ratios when tested under the WC condition, but the lowest I/O ratios under the WC + HECA condition (Fig. 2). It should be noted that WC and WC + HECA only used outside air mode. The highest I/O under WC and the lowest I/O under WC + HECA suggest that switching cabin

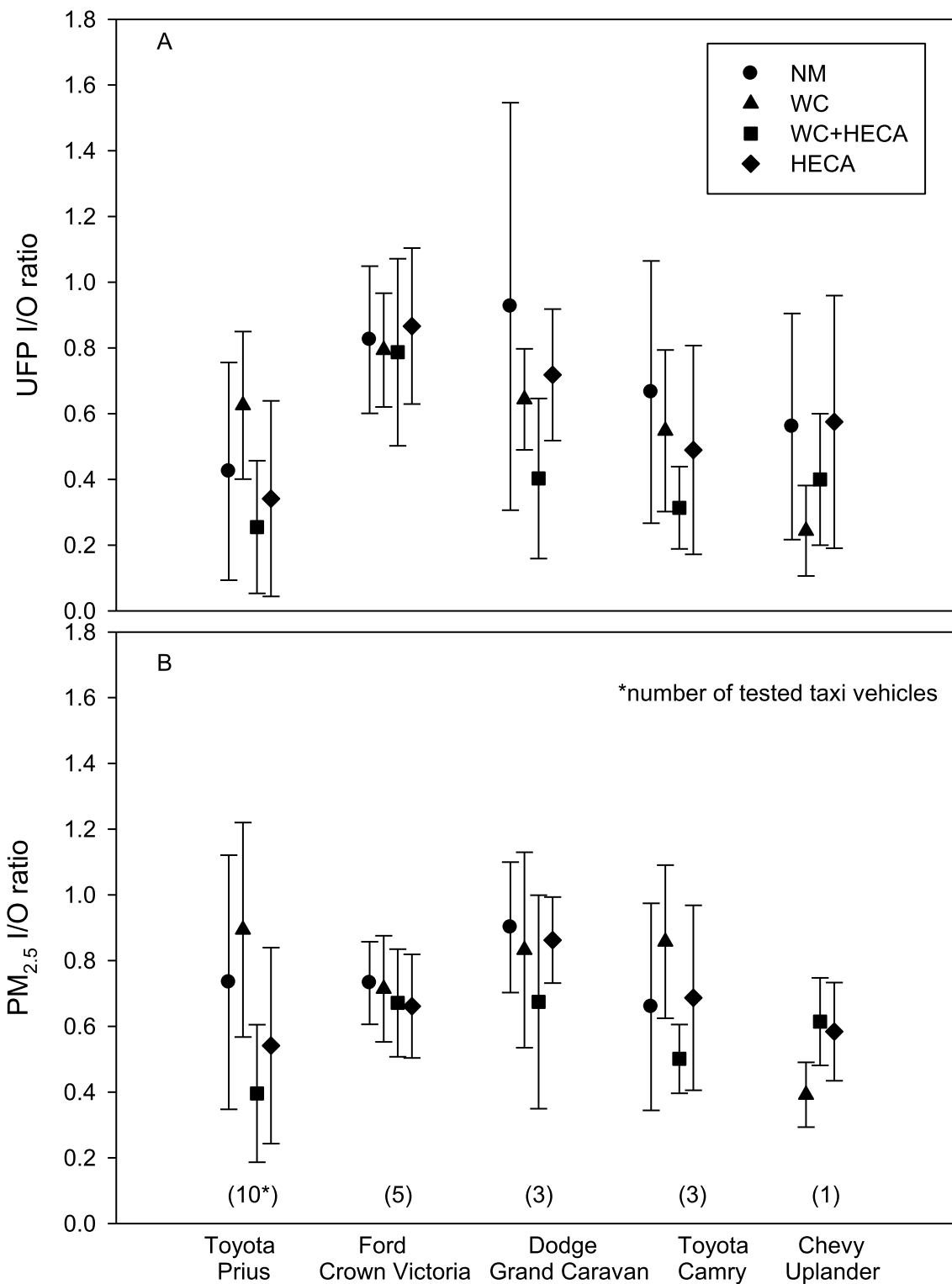


Fig. 2. (a) UFP and (b) PM<sub>2.5</sub> I/O ratios for different taxi vehicle models. NM indicates “no mitigation”, WC indicates “window closed with outside air mode”, and HECA indicates “high efficiency cabin air filter in use”.

air filters from OEM to HECA reduced particle levels in Toyota Prius taxis more substantially than other taxi models.

Air filter collection efficiency (E) is defined as  $E = \frac{C_{pre-filter} - C_{post-filter}}{C_{pre-filter}}$ , where  $C_{pre-filter}$  and  $C_{post-filter}$  are the particle concentrations in air entering and leaving the filter, respectively. However, unlike the laboratory testing environment, the in-cabin particle concentration is not the same as the  $C_{post-filter}$  because the outside air may enter the cabin

through gaps and cracks. Besides filter collection, particle deposition onto the vehicle interior surfaces could also lead to particle losses (Gong et al., 2009). If we assume different taxis had the same HECA filter collection efficiency and similar surface deposition rate, the lowest I/O under WC + HECA indicates that Toyota Prius taxis were less leaky than others. However, it should be noted that the HECA filter efficiency is also affected by the ventilation system design, the filter size/topology, and the instant pressure drop through the filter. Due to

limitations in the field, the collection efficiency of each filter used in this study cannot be determined.

There has been a trend of switching taxi models to Toyota Prius because it is a hybrid vehicle with low emission and high mileage per gallon (MPG). In fact, the tested Toyota Prius taxis did have more recent model years (Table 1). The results of this study suggest that improving the cabin filter is a more effective strategy to reduce both UFP and PM<sub>2.5</sub> levels inside the Toyota Prius than other tested taxi models, thus, support this switching trend.

### 3.5. Other factors affecting in-cabin UFP and PM<sub>2.5</sub>

Our previous study found that besides window positions and ventilation settings, car model, driving on freeway or local streets, driving speed, and car age/mileage also affect taxi AERs (Shu et al., 2015). Since the AERs are one of the determinants of the I/O ratios, those factors were investigated in this study as well. The collected data were further cleaned up before the regression analysis: (i) the NM and HECA data were excluded because the window positions and ventilation settings were not consistent during those tests which may bias the 5-min average in-cabin levels and introduce uncertainties in the regression results; (ii) the Ford Crown Victoria taxis were excluded from this regression analysis because they had significantly higher AERs (Shu et al., 2015; Fruin et al., 2011) and no mitigation effects. The Chevy Uplander taxi was also excluded because only one in this model was tested, and the measurements were not complete. Finally, the WC and WC + HECA data collected from the 10 Toyota Prius, 3 Toyota Camry, and 3 Dodge Grand Caravan taxis were used to fit the mixed effect linear regression model expressed in Equation (1), which analyzes the associations between the in-cabin UFP and PM<sub>2.5</sub> concentrations and the different influencing factors, taking the individual taxi vehicle and driver effects into consideration. The models with the lowest Bayesian information criteria (BICs) were selected as the final model, and the results are summarized in Table 3.

In the mixed effect models, car age is calculated as the number of years between the car model year and 2013, mileage is the odometer reading in mile on the first vehicle test day, and speed is the vehicle driving speed in km h<sup>-1</sup>. Mitigation and car model are treated as categorical variables indicating mitigation conditions such as WC and WC + HECA, and taxi models such as Toyota Prius, Toyota Camry, and Dodge Grand Caravan. WC was used as the reference category for mitigation, and Toyota Prius was used as the reference category for car model. The R values in Table 3 indicate the intraclass correlation coefficients (ICCs) of the random effect.

The results show that in-cabin UFP and PM<sub>2.5</sub> concentrations are

significantly associated with on-road levels, vehicle driving speeds, and mitigation conditions (WC and WC + HECA) (*p* < 0.01). Car age is a significant factor for in-cabin UFP but not PM<sub>2.5</sub>. Unlike the other factors, both car age and WC + HECA show negative associations with the in-cabin UFP and PM<sub>2.5</sub>, which means when other conditions held the same, the in-cabin levels are reduced when the car age increases or the filter is switched from OEM to HECA. This is likely because the OEM filters in most of the tested taxi vehicles were not replaced for years before the tests and the particle loads on the OEM filters enhanced the filtration efficiency. Changing to a higher efficiency filter introduces the similar effects for in-cabin UFP and PM<sub>2.5</sub> levels. The resulted positive correlations between in-cabin levels and on-road concentrations are consistent with our observations in Fig. 1, which shows the similar temporal trends between on-road and in-cabin concentrations. Positive correlation was also found between in-cabin PM and driving speed, suggesting when the driving speed goes up, the in-cabin levels go up while other conditions are held the same, which is consistent with previous studies in regular passenger vehicles (Hudda and Fruin, 2013; Shu et al., 2015; Fruin et al., 2011). It should be noted that the significant correlations were only observed under the “window closed with outside air ventilation mode” condition. Mileage and car model (Toyota Prius, Toyota Camry, and Grand Caravan) are not strong predictors of in-cabin concentrations in these models. The different R values indicate that for the same vehicle, the correlation is greater for PM<sub>2.5</sub> than for UFPs. This is also consistent with our observation that in-cabin UFP concentrations fluctuated in greater ranges than PM<sub>2.5</sub> for the same taxi (Fig. 1).

### 3.6. Comparison with passenger vehicles

The taxis tested in this study had approximately twice as much mileage (Shu et al., 2015) as passenger vehicles of the same age reported in a previous study (Fruin et al., 2011). Therefore the tested taxis are expected to have more wear and tear and are likely to be leakier than regular passenger vehicles. It is reasonable to expect that the AER and I/O ratios of taxis are generally higher than those of regular passenger vehicles.

The mitigation strategies were found to be effective in reducing both UFP and PM<sub>2.5</sub> inside taxis, but the reduction rates were not as high as previously reported in passenger vehicles. Lee and Zhu reported that the HECA filters from the same industrial partner reduced passenger vehicle in-cabin UFP and PM<sub>2.5</sub> levels by 92% and 70% respectively (Lee and Zhu, 2014). Fig. 3 compares the results of this taxi study with the study by Lee and Zhu on passenger vehicles (Lee and Zhu, 2014). Generally speaking, the on-road UFP and PM<sub>2.5</sub> levels were higher but

**Table 3**  
Coefficients of mixed effect linear model for in-cabin UFP and PM<sub>2.5</sub> levels.

	In-cabin UFP			In-cabin PM <sub>2.5</sub>		
	Estimate	Std. Err.	P-value	Estimate	Std. Err.	P-value
Intercept	0.82	0.38	0.07	-2.30	0.30	< 0.01
On-road	0.84	0.03	< 0.01	0.45	0.04	< 0.01
Car age	-0.07	0.03	0.01	-0.02	0.05	0.71
Mileage	2.34 × 10 <sup>-6</sup>	1.54 × 10 <sup>-6</sup>	0.13	2.82 × 10 <sup>-7</sup>	2.50 × 10 <sup>-6</sup>	0.91
Speed	1.86 × 10 <sup>-3</sup>	5.77 × 10 <sup>-4</sup>	< 0.01	1.17 × 10 <sup>-3</sup>	3.17 × 10 <sup>-4</sup>	< 0.01
Mitigation						
WC <sup>a</sup>	-	-	-	-	-	-
WC + HECA	-0.72	0.04	< 0.01	-0.68	0.02	< 0.01
Car model						
Toyota Prius <sup>a</sup>	-	-	-	-	-	-
Toyota Camry	0.06	0.14	0.65	0.21	0.24	0.40
Dodge Caravan	0.28	0.19	0.14	0.11	0.33	0.73
R <sup>b</sup>	0.10	-	-	0.53	-	-

<sup>a</sup> Reference categories.

<sup>b</sup> Intraclass Correlation Coefficient (ICC).

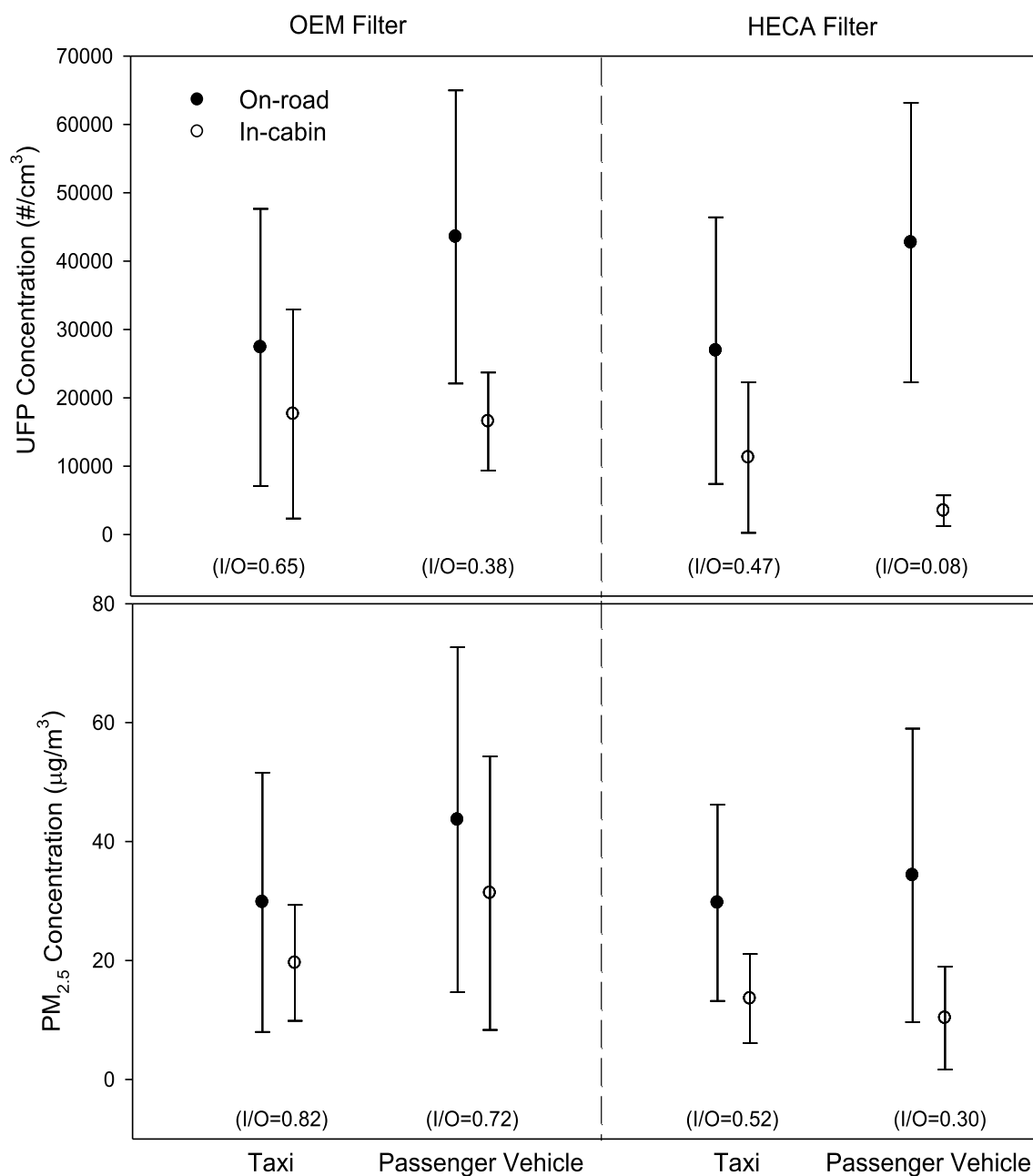


Fig. 3. Comparison with passenger vehicles (Lee and Zhu, 2014) for on-road and in-cabin UFP and PM<sub>2.5</sub> concentrations with OEM and HECA filters. The error bars indicate one standard deviation. Average I/O ratios were calculated and marked in parentheses.

the in-cabin levels were lower in the passenger vehicles study than in the current taxi study (Fig. 3). The calculated average I/O ratios were always lower in the passenger vehicles than in the taxis. In addition, the UFP and PM<sub>2.5</sub> I/O reductions in passenger vehicles from using the OEM filter to using the HECA filter were over 60% higher than in taxis. This is mainly because the passenger vehicles tested in the study by Lee and Zhu were all less than three years old and more likely to be better maintained than the taxis. By comparison, 17 out of the 22 taxi vehicles tested in this study were older than three years, and about half of them were older than five years. Furthermore, the mileage on taxi vehicles was much higher, indicating they were more worn than regular vehicles of the same age (Shu et al., 2015; Fruin et al., 2011). Thus, the leak from the gaps around the HECA filter inside the ventilation system or from the cracks on doors, windows, and trunks may be higher in taxis than in the passenger vehicles.

### 3.7. Study limitations

A total of 22 taxis were tested in this study, and thus, the number of each model was small. Some unpopular taxi models were not sufficiently sampled due to the stratification method. The ventilation settings and window positions were not recorded during the NM and HECA tests, but the window closed with recirculation mode (RC + WC) condition was identified for all of the NM tests. However, other ventilation and window position combinations cannot be differentiated. Finally, the day-to-day meteorology and traffic variations could not be fully controlled. In particular, although the ambient temperature fluctuated in a relatively low range in Los Angeles with recorded readings during the field sampling of  $26.6 \pm 6.9$  °C (mean  $\pm$  SD) (Table S2), it may have affected the decision on to open windows when they were allowed to do so. Nevertheless, results from this study clearly indicate that controlling the window position and ventilation setting and

improving cabin air filters are promising methods to reduce UFP and PM<sub>2.5</sub> levels inside taxis.

#### 4. Conclusions

On average, Los Angeles taxi drivers are exposed to  $1.46 \times 10^4$  particles/cm<sup>3</sup> of UFP and 26 µg/m (Zhu et al., 2007) of PM<sub>2.5</sub> while driving on the roadways without mitigation. The four ventilation and mitigation conditions of NM, WC, WC + HECA and HECA reduced the on-road UFP levels by 40%, 35%, 53%, and 49%, and reduced on-road PM<sub>2.5</sub> levels by 25%, 34%, 48%, and 39%, respectively. UFP and PM<sub>2.5</sub> levels inside taxis as well as their I/O ratios were significantly different under each of the four conditions. UFP and PM<sub>2.5</sub> had the lowest I/O ratios, 0.47 and 0.52, under the WC + HECA condition. The results show that simply closing taxi windows (WC) but using outside air ventilation mode did not effectively reduce UFP and PM<sub>2.5</sub> I/O ratios in Toyota Prius taxis. The HECA filter reduced the PM in Toyota Prius taxis most substantially across all tested taxi models. Factors significantly affecting the in-cabin UFP levels include the on-road concentrations, driving speed, and mitigation strategy, while the significant factors affecting the in-cabin PM<sub>2.5</sub> include on-road levels, driving speed and mitigation strategy.

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#### Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.atmosenv.2018.03.023>.

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