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Measuring and modeling air exchange rates inside taxi cabs in Los Angeles, California

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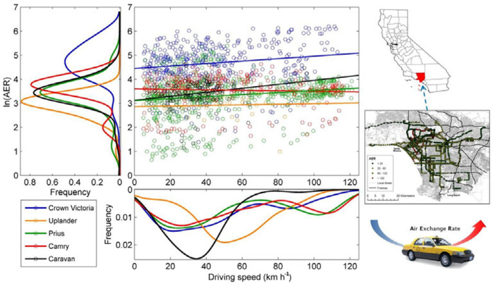
HIGHLIGHTS

- Air exchange rates in 22 representative Los Angeles taxi cabs were quantified.
- AERs under realistic driving condition had a mean of 63 h^{-1} and a median of 38 h^{-1}.
- AERs were significantly higher when driving on freeways than on local streets.
- With medium fan speed under outdoor air mode, average AERs increased 32%.

GRAPHICAL ABSTRACT



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ABSTRACT

Air exchange rates (AERs) have a direct impact on traffic-related air pollutant (TRAP) levels inside vehicles. Taxi drivers are occupationally exposed to TRAP on a daily basis, yet there is limited measurement of AERs in taxi cabs. To fill this gap, AERs were quantified in 22 representative Los Angeles taxi cabs including 10 Prius, 5 Crown Victoria, 3 Camry, 3 Caravan, and 1 Uplander under realistic driving (RD) conditions. To further study the impacts of window position and ventilation settings on taxi AERs, additional tests were conducted on 14 taxis with windows closed (WC) and on the other 8 taxis with not only windows closed but also medium fan speed (WC-MFS) under outdoor air mode. Under RD conditions, the AERs in all 22 cabs had a mean of 63 h^{-1} with a median of 38 h^{-1}. Similar AERs were observed under WC condition when compared to those measured under RD condition. Under WC-MFS condition, AERs were significantly increased in all taxi cabs, when compared with those measured under RD condition. A General Estimating Equation (GEE) model was developed and the modeling results showed that vehicle model was a significant factor in determining the AERs in taxi cabs under RD condition. Driving speed and car age were positively associated with AERs but not statistically significant. Overall, AERs measured in taxi cabs were much higher than typical AERs people usually encounter in indoor environments such as homes, offices, and even regular passenger vehicles.

1. Introduction

Previous studies have found that, for the general U.S. population that spends on average 1.3 h driving each day (Klepeis et al., 2001), 17–50% of their total daily ultrafine particles (UFPs)

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exposure is from in-vehicle exposures (Fruin et al., 2008; Wallace and Ott, 2011; Zhu et al., 2007). For taxi drivers, this in-vehicle percent of daily UFP exposure is likely much higher because, on average, they work six days per week and spend 7–12 h each day on driving (LA DOT, 2010). Previous studies have shown that professional drivers have high occupational exposure to traffic-related air pollutant (TRAP) (Gustavsson et al., 2000), which is also reflected by different biomarkers (Brucker et al., 2013; Gustavsson et al., 1996). Therefore, Knibbs and Morawska (2012) pointed out there is a great potential to link the exposure science and epidemiology by studying professional drivers' exposure and illness.

Air exchange rate (AER) is a factor that affects the air quality in a defined space, in this case, the taxi cabin (Chan and Chung, 2003; Knibbs et al., 2010). Higher AER leads to lower concentrations of air pollutants that are originated indoors and higher concentrations of air pollutants that are originated outdoors. In the case of motor vehicles, higher AER would result in higher in-cabin concentrations of TRAPS and lower concentrations of in-cabin-originated compounds such as phthalates (Geiss et al., 2009) and alkanes (You et al., 2007). Therefore the AERs in the cabin would impact the drivers' occupational exposure to different types of air pollutants in different ways. Quantifying the AERs in taxi cabins would lead to better understanding of taxi drivers' occupational exposure to air pollutants from different sources. Several studies have measured the AER in regular passenger vehicles (Fletcher and Saunders, 1994; Knibbs and de Dear, 2010; Knibbs et al., 2010). For example, Ott et al. (2008) measured AERs in four motor vehicles at six different driving speeds ranging from 20 to 72 mph (32–116 km h^{-1}). With windows closed and ventilation system off, the AER was less than 6.6 h^{-1}. They also found that the position of windows, air conditioning (AC) system settings, driving speed, car model, and car age all have significant effects on AER. Fruin et al. (2011) successfully built a statistical model to predict vehicle AER using car age, mileage, manufacturer, and driving speed, based on measurements conducted in 59 passenger vehicles at three different speeds. According to this model, a typical California passenger vehicle manufactured in 2010 would have AER of 20 h^{-1}, when driving at speed of 105 km h^{-1}. However, these studies were conducted under controlled experimental conditions, so that some of the influencing factors such as driving speed, windows position, and air conditioning settings were arbitrarily selected. Therefore, it is expected that AERs published in the literature may not reflect true AER values for taxis, because these influencing factors are changing frequently under realistic driving conditions.

In addition, the characteristics of taxi cabs are potentially quite different from those of regular passenger vehicles. For example, taxi cabs are likely to have higher mileages than regular passenger vehicle of same age and tend to be leakier because of excessive wear and tear. Consequently the AERs for taxis under realistic driving conditions are not fully understood. Previous studies conducted on passenger vehicles may not sufficiently represent the AERs in taxi cabs (Fletcher and Saunders, 1994; Fruin et al., 2011; Knibbs et al., 2009; Ott et al., 2008).

To fill this data gap, the first objective of this study is to measure the AERs in a number of representative taxi cabs under realistic driving (RD) conditions, to quantify the typical AERs experienced by taxi drivers in the Greater Los Angeles area. The second objective is to investigate if keeping windows closed (WC) and/or using medium fan speed (MFS) would significantly change the AERs in taxi cabs. A GEE model based on measurement data is used to analyze the importance of various factors that influence AERs. The measured AERs and modeling results may be applied to other taxi cabs in the Greater Los Angeles area.

2. Methods

2.1. Taxi cab recruitment

A recruitment/survey campaign was conducted at the Los Angeles Airport (LAX) taxi holding lot from February 11th to 15th, 2013, in order to recruit study participants and collect basic information about taxi drivers and their cabs. A questionnaire that included 10 questions about age, race, smoking history, car model, car age, and driving related behavioral factors was designed and used for the recruitment/survey campaign (see Supplementary Material Fig. S1). A total of 2449 survey forms were handed out and 316 complete survey forms were collected. The descriptive statistics of these 316 survey forms are also provided in the Supplementary Material Table S1. Out of these 316 taxi drivers, 121 non-smokers were eligible to participate in this study. To ensure the sampled taxi drivers/cabs are representative, stratified random sampling was conducted based on car models and drivers' age. Drivers' age was considered as a factor for stratified random sampling because previous studies have found that drivers of different ages have different driving patterns (Horberry et al., 2006), which affect both the in-cabin air exchange rates (Hudda et al., 2011) and the vehicles' pollution emissions (Ericsson, 2001). A total of 22 taxi drivers/taxi cabs out of 121 eligible drivers were selected to participate in this study. The study design and protocol have been approved by the Institutional Review Board (IRB) of University of California Los Angeles. In terms of vehicle models, the 22 taxi cabs included 10 Prius, 5 Crown Victoria, 3 Camry, 3 Caravan, and 1 Uplander.

2.2. Experiment design

Each experiment consisted of four consecutive test days with one driver and his or her taxi cab. On each test day, the driver drove 6 h 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 starting time of each day was based on the driver's availability and kept consistent for each driver during the four test days in order to minimize the differences in traffic conditions and meteorological conditions among the four test days. No actual fares were collected during the tests and the drivers' time and efforts were compensated by the research funding. Each driver was allowed to take breaks as he or she would during a typical work day. 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 driving routes were not specifically planned for each driver. Instead, on the first test day, each driver was asked to drive from the start location, University of California Los Angeles, to the area where he or she usually works and repeat what he or she did in the previous day. The same route was used as much as possible for the following three test days, to minimize the difference among different days. 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 testing. The total mileage driven by the 22 taxi drivers in this study was approximately 11,000 km and the total hours of field measurement was approximately 500 h.

Three experimental conditions: realistic driving (RD), windows closed (WC), and windows closed with medium fan speed (WC-MFS) were used in this study. Under RD condition, everything was kept as close 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 under RD condition best represent the AERs experienced by Los Angeles taxi drivers during their everyday job. Under WC condition, the taxi drivers were required to keep all the windows closed during the 6 h measurement, but the taxi drivers had control over AC and ventilation mode. WC condition was used to investigate whether keeping windows closed all the time could reduce the AER in a taxi cabin. Under WC-MSF condition, the taxi drivers were not only required to keep all the windows closed but also keep the ventilation fan at mid-level under outdoor air mode throughout the 6 h measurement. However, the drivers were allowed to turn the AC on or off to achieve a thermally comfortable environment in the taxi cabin. The operation of AC only affects the working status of the air heating/cooling components and does not change the air flow in the ventilation system, therefore has minimum impacts on AERs. For the first 14 drivers, RD and WC conditions were used, each for 2 days. While for the rest 8 drivers, RD and WC-MFS conditions were used, each for 2 days.

2.3. AER measurements

The AER measurements were conducted by using CO_2 as a tracer gas, a method which has been proven to be relatively easy yet accurate in regular passenger vehicles (Fruin 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 CO_2 concentrations. One Q-Trak had its probe placed outside, usually attached to the top of taxi cab, to measure the on-road CO_2 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. Previous studies have shown that the well-mixed condition of in-cabin CO_2 can be assumed (Fruin et al., 2011; Hudda et al., 2011; Lee and Zhu, 2014). Both Q-Traks were reading and recording CO_2 concentrations at one second time resolution. Later on these CO_2 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 CO_2 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 CO_2 mass balance in the taxi cabin was built, as shown in Equation (1).

$$V\frac{dC_i}{dt} = E + QC_o - QC_i \tag{1}$$

where V is the volume of cabin in m^3, which is reported by the vehicle manufacturer, C_{in} and C_o are the in-cabin and on-road CO_2 concentrations in mg m^{-3}, respectively, E is the emission rate of CO_2 in the cabin in mg min^{-1}, and Q is the air flow rate from outside into the cabin in m^3 min^{-1}. By rearranging Equation (1) and using its discrete form, Equation (2) was obtained and used to calculate the AER at time t.

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

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 CO_2 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 CO_2 per minute (McArdle et al., 2010), which equals to one adult generating 900 g of CO_2 in a day. The authors are aware of the uncertainty in this respiration CO_2 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 ±16%. Since the calculated AERs were linearly related to the E, the uncertainty in calculated AERs was approximately ±20%, taking other uncertainties, such as the ±10% accuracy of Q-Trak readings, into account.

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).

2.4. AERs under WC and WC-MFS conditions

To explore how the operations on taxi cabs' windows and ventilation fan affect AERs for each individual taxi, the geometric means of AERs in individual taxi cabs under different conditions were calculated and then the paired two-sample Wilcoxon test was used for statistical inference.

2.5. GEE model for AERs

A Generalized Estimating Equation (GEE) model was developed to analyze the importance of different factors that can potentially impacts 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 (Fruin et al., 2011; Knibbs et al., 2009). As previously found (Fruin 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 units, in this case, the taxi cabs. 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. Results and discussion

3.1. Characteristic of taxi cabs

The data collected from the survey questionnaires demonstrated that taxi cabs have higher mileages than a passenger vehicle of the same age. As shown in Fig. 1, a Los Angeles taxi cab has approximately twice as many mileages as a regular California passenger vehicle of the same car age. Therefore the taxi cabs are expected to have more wear and tear, and are likely to be leakier than regular passenger vehicles.

The 22 tested taxi cabs have a similar distribution of car model when compared with the surveyed results from the recruitment campaign. The Toyota Prius and Ford Crown Victoria are the two

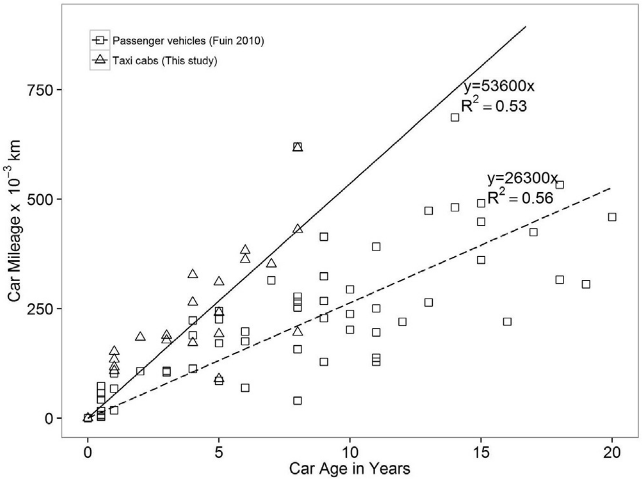

Fig. 1. Relationship between car age and car mileage, comparing taxi cabs and representative passenger vehicles.

most popular car models among Los Angeles taxi cabs. The five car models tested in this study — Prius, Crown Victoria, Camry, Caravan, and Uplander — comprised 86% of all types of taxis in Los Angeles.

For drivers' working pattern and habits of operating windows and ventilation system, the questionnaires showed that the taxi drivers work 6.1 ± 0.8 days per week and 11.9 ± 2.3 h on each working day, and 18% of taxi drivers spend more than 6 h each day driving on freeways. In addition, 56% of taxi drivers keep their windows open for at least half of their work time. However, field technicians observed that, five of the taxi drivers kept the windows closed for roughly 90% of total testing hours even during the RD condition test. It is possible that the taxi drivers' behaviors were affected by the experiment and they closed windows more than they usually do on their job. If this can be confirmed, the AERs measured under RD condition in this study may underestimate the AERs taxi drivers experience on their job.

3.2. Measurement results

3.2.1. CO_2 concentration profiles

Typical one-minute averaged in-cabin and on-road CO_2 concentrations as well as the driving speed are shown in Fig. 2.

During this period, there are two people inside the taxi with an estimated CO_2 emission rate of 0.68 L per minute. As shown in Fig. 2, the driving speed increased and the in-cabin CO_2 concentration decreased around 20:45, but the on-road CO_2 concentrations remained relatively stable. This suggests higher driving speed led to higher AER which reduced the in-cabin CO_2 concentrations.

3.2.2. AERs under RD condition

Fig. 3 shows the map of the driving routes covered in this study and the spatial distribution of AERs measured under RD condition. There is no clear spatial clustering pattern of the data, indicating that the location is not an important factor in determining the AERs. The relationship between driving speed and AERs measured under RD condition for all 22 cabs are presented in Fig. 4, which is a scattered plot with the distribution for both axes. In general, taxi driving speeds (the x axis) had two modes corresponding to 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. The descriptive statistics of AERs measured under RD condition are shown in Table 1.

3.2.3. AERS under WC and WC-MFS conditions

Fig. 5 shows the comparison between AERs measured under RD condition with those measured under WC condition and WC-MFS condition. Fig. 5a shows that WC conditions had AERs that are not significantly different with those under RD conditions in this study. This is possibly due to the fact that most drivers kept their windows closed even during their RD condition test, as observed by the field technicians. Previous studies have found that closing windows can reduce AERs in vehicle cabins, when other operation conditions held constant (Esber et al., 2007; Fruin et al., 2011; Ott et al., 2008; Park et al., 1998). It is reasonable to believe that, for those taxi drivers who open their cab windows often on their job, closing windows can potentially shelter them from high AERs and high TRAP concentrations. Compared with the RD condition, the WC-MFS condition significantly increased the AERs in taxi cabs. Based on data collected from the eight taxi cabs (Fig. 5b), the mean AERs under WC-MFS condition, 37 h^{-1}, was 32% higher than those measured on RD condition, which was 28 h^{-1}. This finding highlighted the importance of improving the cabin filter efficiency to mitigate the taxi drivers' occupational TRAP exposure (Lee and Zhu, 2014).

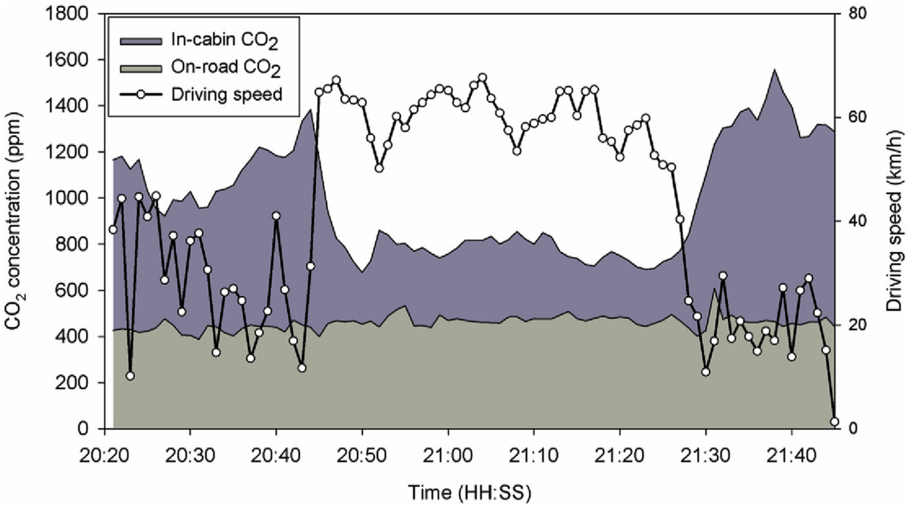

Fig. 2. Typical in-cabin and on-road CO_2 concentrations and driving speeds.

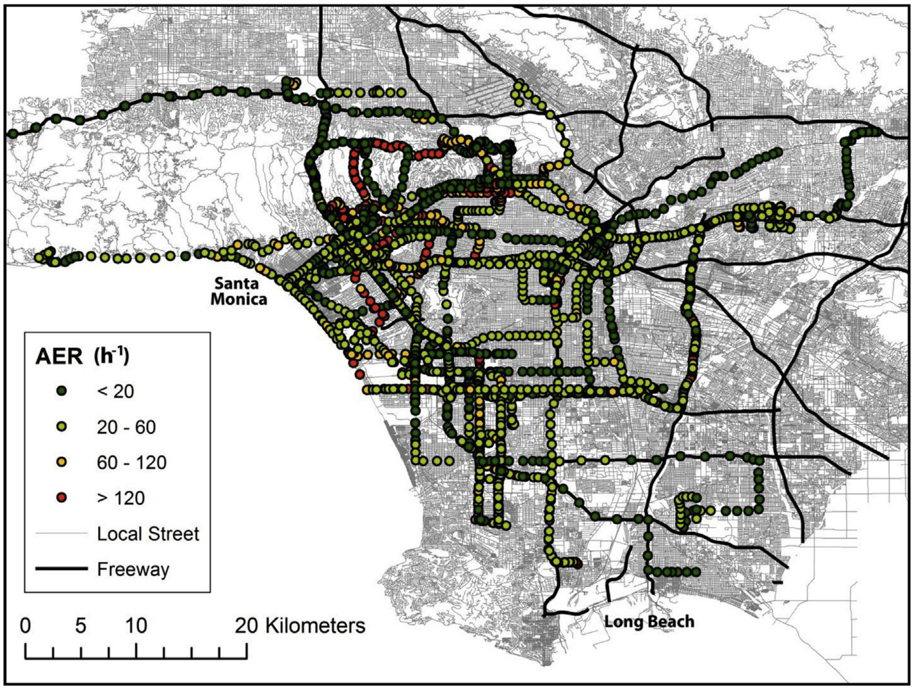

Fig. 3. Map of driving routes and the spatial distribution of AERs measured under RD condition.

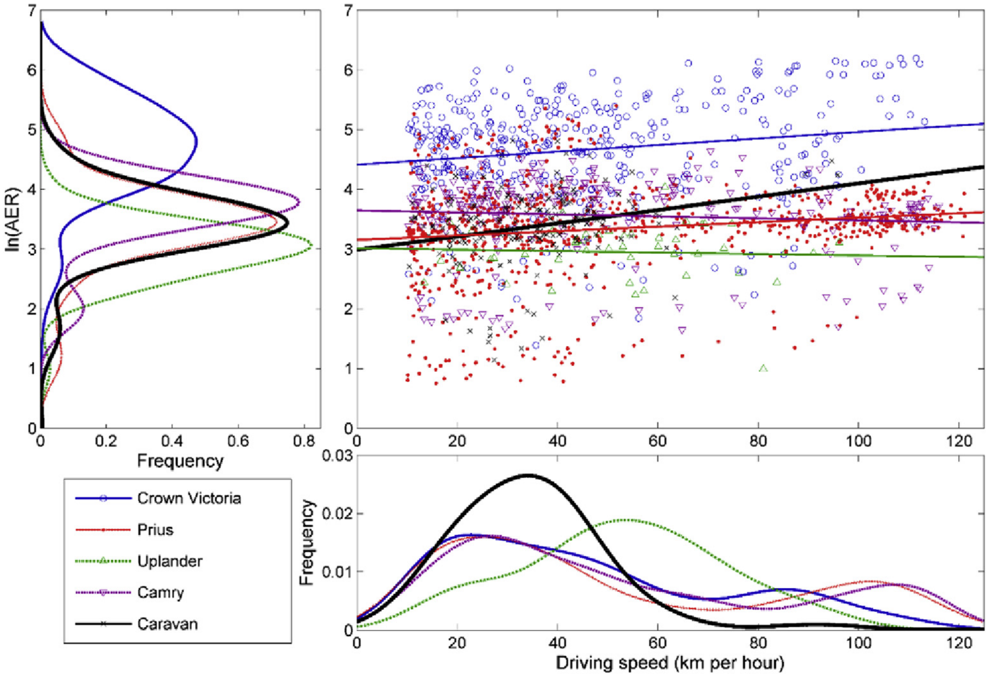

Fig. 4. Log-transformed air exchange rates and its relationship with driving speed, grouped by car models. Air exchange rates were measured under RD condition.

3.2.4. *Comparing AERs obtained on local streets and freeways*

After log-transformation was performed on AERs, Welch's t-test was used to test if the AERs obtained from freeways and local streets are significantly different. As shown in Fig. 6, the AERs obtained on freeways were statistically higher than those obtained on local streets, in all three experimental conditions. This finding suggested that the taxi drivers are experiencing higher exposure to TRAP when driving on freeways, since not only AER but also the air pollutant levels are also usually higher on freeways than on local streets (Quiros et al., 2013; Shu et al., 2014; Zhu et al., 2007). Therefore, using TRAP mitigation methods in taxi cabs, especially when driving on freeways, would be important to reduce the occupational exposure to TRAP (Lee and Zhu, 2014).

3.3. *Modeling results*

The GEE model with the lowest QIC, which was selected as the final model, is presented by Equation (3).

Table 1
Summary of characteristics of tested taxi cabs and air exchange rates measured under RD condition.

Car model	Number of vehicles	Mileage [10^{-3} km ± SD]	Car age [Years ± SD]	AER under RD condition[a] [h^{-1}]				
				n[b]	Mean	25%	50%	75%
Camry	3	190 ± 74	2.3 ± 1.5	528	37.0	14.7	41.3	82.3
Caravan	3	283 ± 132	3.7 ± 2.5	502	18.9	13.6	24.0	32.8
Uplander	1	433 ± 0	8.0 ± 0	158	26.8	16.4	28.2	49.4
Crown Victoria	5	446 ± 151	7.0 ± 1.0	1126	75.2	41.3	78.3	148.4
Prius	10	184 ± 63	4.0 ± 2.1	2057	18.9	7.1	25.5	39.6

[a] AER is in unit of h^{-1} before log transformation.
[b] Number of 5-min average AER values.

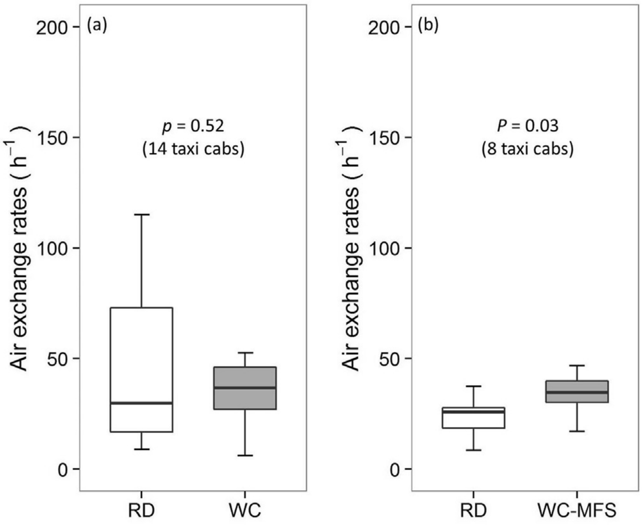

Fig. 5. Air exchange rates measured under RD condition compared with those measured under WC condition and WC-MFS condition, respectively. Each point represents the geometric mean of AERs obtained in one taxi cab under different conditions.

$$ln(AER) = \beta_0 + \beta_1 \times Speed + \beta_2 \times CarAge + \beta_3 \times Mileage + \beta_4 \times CarMode + \varepsilon_i \quad (3)$$

where *AER* is the observed air exchange rates in h^{-1}, *Speed* is the driving speed in $km\ h^{-1}$, *CarAge* is a continuous parameter which is the number of years between the car model year and 2014, *Mileage* is the odometer reading converted into 10^3 km, ε_i is the adjustment for individual taxi cab/driver combination, and *CarModel* is a categorical parameter that has five levels: Camry, Caravan, Uplander, Crown Victoria, and Prius. Prius was used as the reference category. Independence correlation structure was used in the model for repeated measures. Measurement data obtained under RD condition were fitted in Equation (3) to obtain model parameters. The coefficients are listed in Table 2.

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 under RD condition. 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 showing higher AERs when driving on freeways, where the speed was also higher than on the local streets. It is consistent with the findings in previous studies on passenger vehicles (Fruin et al., 2011; Park et al., 1998). 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

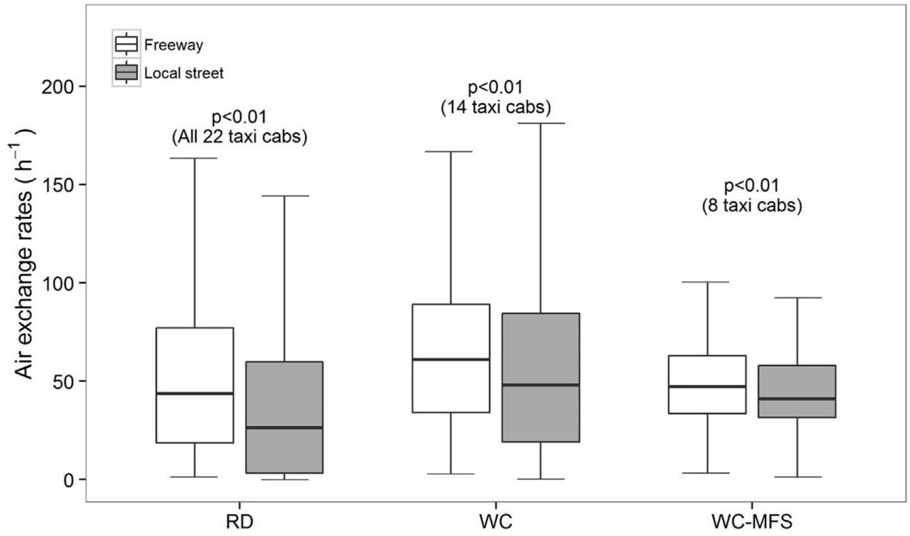

Fig. 6. Comparison between air exchange rates obtained while driving on freeways and on local streets.

Table 2
Coefficients of generalized estimating equations model for AERs measured under RD condition.

	Estimate	Std. Err.	*p*-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[a]	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
CarModle: 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.

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), 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 the same workday.

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 also consistent with one of previous studies which demonstrated that passenger vehicles manufactured by GM and Ford also had significantly higher AERs than vehicles manufactured by Japanese companies (Fruin 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.

3.4. *Implications for occupational exposure*

Under high AER conditions, on-road air enters the taxi cabin at a higher flow rate, carrying TRAP into the cabin. Because taxi drivers spend substantial amounts of time driving, their occupational exposure to TRAP could be orders of magnitude higher than the general population (Knibbs et al., 2010). Two pollutants of particular concern are UFPs and particle-bound polycyclic aromatic hydrocarbons (PB-PAH) (Brucker et al., 2013). These two pollutants are generated by the fuel burning process in motor vehicles engine thus have the highest concentrations on the road (Hu et al., 2009; Zhu et al., 2002). Further studies on the in-cabin air pollutants concentrations and in-cabin-to-on-road (I/O) ratios are necessary for more accurate occupational exposure assessment (Hudda et al., 2012). On the other hand, the high AERs could lower the concentrations of some air pollutants originated inside taxi cabins, for example, phthalates, and thus reduce the taxi drivers' occupational exposure to these chemicals.

Based on the GEE modeling results, switching to taxi cabs of certain models could be an effective way of reducing the AERs experienced by taxi drivers on their daily job, therefore reduce their occupational exposure to TRAP. In fact, this change in taxi cab models is happening in the Greater Los Angeles area, mainly due to the fact that certain vehicle models (i.e. Prius) have higher fuel efficiency than some old models (i.e. Crown Victoria). Thus, a gradual decrease in the Los Angeles taxi drivers' occupational exposure to TRAP can be expected.

Air leakage could be an important source of in-cabin exposure to TRAP. If this is further confirmed, using additional high efficiency air filtering system inside taxi cabs may be a better TRAP exposure mitigation method compared with the existing in-ventilation-duct air filtering method, since a large portion of on-road air are not filtered while entering vehicle cabin (Lee and Zhu, 2014).

3.5. *Study limitations*

The authors are aware of several limitations of this study. First, more stringent method of determining the CO_2 emission rates of each taxi driver could have been used to increase the accuracy of calculated AERs. To avoid overestimating the AERs, a relatively conservative value of CO_2 emission rate, 0.34 L CO_2 per minute per person was used. Second, the Greater Los Angeles area has a year-round moderate-to-warm weather, which could lead to more frequent window-opening in taxi cabs when compared to areas that have much hotter or colder weather. Therefore cautions should be exercised when extrapolating the AERs data obtained in this study to taxi cabs in other cities.

4. Conclusions

Under the realistic driving (RD) condition, the AERs in the 22 tested Los Angeles taxi cabs had a mean of 63 h^{-1} with a median of 38 h^{-1}. Closing windows did not significantly reduce the AERs in taxi cabs, as the AERs under WC condition were not significantly different from those under RD condition. This is potentially due to the fact, which has been confirmed by the field observation, that most drivers kept their windows closed for most of the time even in the RD condition test. Using WC-MFS condition led to higher AERs in taxi cabs, when compared with those measured under RD condition. Driving speed was positively correlated to AERs although not statistically significant. Crown Victoria and Uplander showed significantly higher AERs compared with other three cab models, based on the GEE model results, suggesting switching to models such as Prius could potentially reduce the taxi drivers' occupational exposure to TRAP. In all three experimental conditions, AERs obtained on freeways were statistically higher than those obtained on local streets, suggesting driving on freeways can cause higher exposure to TRAP.

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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.2015.10.030.

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