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

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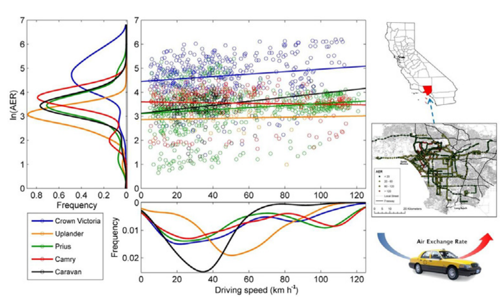
HIGHLIGHTS

- 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