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Comparing on-road real-time simultaneous in-cabin and outdoor particulate and gaseous concentrations for a range of ventilation scenarios

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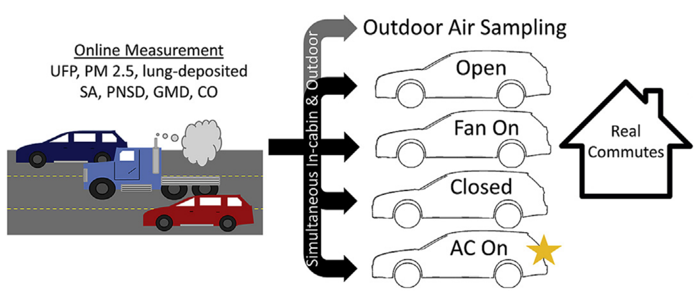
HIGHLIGHTS

- Select pollutants were measured simultaneously outside and inside of an on-road car.
- Multiple predictor variables were examined using linear mixed-effects models.
- Ambient pollutants and meteorological variables explained up to 44% of outdoor variability.
- Outdoor concentrations and ventilation parameters had a strong effect on cabin concentrations.
- Car drivers received higher exposures with windows open or fan on compared to windows closed or AC on.

GRAPHICAL ABSTRACT



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ABSTRACT

Advanced automobile technology, developed infrastructure, and changing economic markets have resulted in increasing commute times. Traffic is a major source of harmful pollutants and consequently daily peak exposures tend to occur near roadways or while travelling on them. The objective of this study was to measure simultaneous real-time particulate matter (particle numbers, lung-deposited surface area, $PM_{2.5}$, particle number size distributions) and CO concentrations outside and in-cabin of an on-road car during regular commutes to and from work. Data was collected for different ventilation parameters (windows open or closed, fan on, AC on), whilst travelling along different road-types with varying traffic densities. Multiple predictor variables were examined using linear mixed-effects models. Ambient pollutants (NO_x, $PM_{2.5}$, CO) and meteorological variables (wind speed, temperature, relative humidity, dew point) explained 5–44% of outdoor pollutant variability, while the time spent travelling behind a bus was statistically significant for $PM_{2.5}$, lung-deposited SA, and CO (adj-R^2 values = 0.12, 0.10, 0.13). The geometric mean diameter (GMD) for outdoor aerosol was 34 nm. Larger cabin GMDs were observed when windows were closed compared to open (b = 4.3, p-value = <0.01). When windows were open, cabin total aerosol concentrations tracked those outdoors. With windows closed, the pollutants took longer to enter the vehicle cabin, but also longer to exit it. Concentrations of pollutants in cabin were influenced by

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outdoor concentrations, ambient temperature, and the window/ventilation parameters. As expected, particle number concentrations were impacted the most by changes to window position/ventilation, and $PM_{2.5}$ the least. Car drivers can expect their highest exposures when driving with windows open or the fan on, and their lowest exposures during windows closed or the AC on. Final linear mixed-effects models could explain between 88 and 97% of cabin pollutant concentration variability. An individual may control their commuting exposure by applying dynamic behavior modification to adapt to changing pollutant scenarios.

1. Introduction

Ambient air pollution is a complex mixture of primary and secondary organic and inorganic particulates and gases generated from both anthropogenic (combustion and non-combustion) and natural sources. Recent estimates have put the global annual mortality rate from ambient particulate matter (PM) pollution at more than 3 million, especially from cardiovascular and circulatory diseases, lower respiratory infections, chronic obstructive pulmonary disorder (COPD), and lung cancer, making it the 9th most important risk factor to human health globally, and the number one environmental risk factor (Lim et al., 2012). The positive association with lung cancer lead, in 2013, to the International Agency for Research on Cancer (IARC) Working Group to unanimously classify outdoor air pollution as carcinogenic to humans (Group 1); PM was evaluated separately and also classified as Group 1 (Loomis et al., 2013). In developed countries, transport contributes 25–40% to ambient pollutant concentrations collectively, although for some pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and ultrafine particles (UFP), traffic may contribute up to 90% (Keuken et al., 2005; Greenbaum, 2013). In fact, diesel and gasoline exhaust have both been classed by the IARC as Group 1 and Group 2B carcinogens, respectively (Russell, 2013). Because traffic emissions are a major source of pollutants, peak concentrations tend to occur near or on roads, which is where an individual may receive a disproportionately large fraction of their total daily personal exposures. Indeed studies have reported elevated risks for developing asthma and reduced lung function in children living near to heavily-trafficked roads (Brugge et al., 2007), as well as measured changes in cardiac biomarkers and pulmonary function in adults driving or working in private vehicles (cars) (Riediker et al., 2004; Heinrich et al., 2005; Sarnat et al., 2014).

Cars continue to dominate the commuting landscape in the US. According to the 2009 National Household Travel Survey (NHTS) conducted by the US Department of Transport (USDOT) (Usdot, 2009), 91% of US commuters travel an average of 24.4 miles (46 min) to and from work by private vehicle; the vast majority (~80%), commute alone (Mckenzie, 2015). Indeed, private vehicle ownership has continued to rise since surveys began in 1969, so that by 2009 the number of personal vehicles far exceeded the number of drivers. In addition, the average age of the US vehicle fleet has also increased so that 40% of all private cars are now 10 years of age or older (Usdot, 2009). This has potential environmental and health consequences given that older vehicles tend to generate higher emissions, due to age-related deterioration of vehicle control systems (Borken-Kleefeld and Chen, 2015), impurity-enriched lubricating oil in the crankcase (Russell, 2013), abrasion and wear and tear of metallic components (Greenbaum, 2013), and generally more permissive emission standards (Krasenbrink et al., 2005). The persistent lack of investment and public support continues to hamper the development of transport alternatives, thus vehicle ownership and traffic flows are only expected to increase.

Many laboratory and field studies have examined pollutant concentrations and commuter exposures during car travel (Kaur et al., 2007; Zuurbier et al., 2010; De Nazelle et al., 2012; Kingham et al., 2013; Ragettli et al., 2013; Suarez et al., 2014; Good et al., 2016). Factors such as vehicle age, fuel type, driving patterns (acceleration/idling), vehicle speed, proximity to other cars, road-type, position on the road, self-pollution, traffic mix, meteorology, topography, and road condition, have all been reported to influence the local pollutant environment outside of a vehicle (Van Wijnen et al., 1995; Knibbs et al., 2010, 2011; Kingham et al., 2013). And although studies investigating car commuting exposures have highlighted elevated cabin pollutant concentrations whilst travelling through tunnels and on freeways (Kaminsky et al., 2009; Knibbs et al., 2010), with both increasing and decreasing vehicle speeds (Hudda et al., 2012; Ding et al., 2016), and higher road and traffic densities (Weichenthal et al., 2015), the air exchange rate (AER) (dependent on ventilation parameters such as window position, the ventilation system (fan/AC), natural leakage from door seals and window cracks) is highlighted as among the most important determinants of cabin concentrations, or cabin particle removal (Hudda et al., 2011; Knibbs et al., 2011). Kaminsky et al. (2009) observed the highest UFP concentrations with AC followed by windows open then windows closed, while Hudda et al. (2012) and Ding et al. (2016) reported lower indoor/outdoor ratios when the fan was operating under re-circulation (compared to non-recirculation) mode. The duration of the commute has also been highlighted when cumulative exposures were considered (Good et al., 2016), something that is often neglected when averages are the main metric with which results are described.

Only a few studies have previously obtained simultaneous in-cabin/outdoor measurements. Hudda and Fruin (2013) collected multiple particle metrics (UFP, $PM_{2.5}$, PM_{10}, black carbon (BC), particle-bound PAHs) during 3 ventilation modes: fan off, fan on (recirculation mode), fan on (outside air). They also conducted earlier studies measuring particle number size distributions (PNSD) and total particle number concentrations (Hudda et al., 2011, 2012). Zhu et al. (2007) also measured in-cabin/outdoor PNSD and particle number concentrations in 3 vehicles for the same ventilation modes as the previous study. Bigazzi and Figliozzi (2012) measured UFP in 3 vehicles for a range of ventilation scenarios, however simultaneous in-cabin/outdoor measurements were only collected during the latter part of the study. Finally, Weichenthal et al. (2015) measured simultaneous in-cabin/outdoor UFP, BC, CO, and $PM_{2.5}$ concentrations in 3 cities in Canada in one vehicle type; however, the different ventilation scenarios were not investigated.

Existing studies provide invaluable insights into the factors controlling cabin concentrations. However, one of the main objectives and largest contributions of this work was to collect/present simultaneously collected in-cabin and outdoor data for multiple pollutant metrics during realistic car commutes. To the authors' knowledge, no other study has incorporated real home-to-